

Dispersion of a fuel spray in a heated channel with controlled turbulence: characterization of droplet temperature and fuel vapor distribution.

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Abstract

Designing new low-emission combustors requires the development of computational codes with high predictive capabilities. Numerical models used in these numerical simulations must be validated against experimental reference cases where the different parameters of interest can be measured and controlled.

This contribution presents experiments where a fuel spray with a known composition is injected in a heated channel where homogeneous and isotropic turbulence is developed. Droplet size and velocity distributions as well as the characteristics of turbulence in the gas flowfield were previously measured. The liquid fuel consists of different mixtures mainly composed of n-decane and a fraction of 3-pentanone varying from 0 to 15 % in volume. Air inlet temperature is 560 K, bulk-flow velocity 2 m/s and turbulence rate about 25 %.

Two laser-based diagnostics are implemented on this experiment in order to characterize both the liquid and the gas phases.

Droplet temperature is first measured with the two-color laser-induced fluorescence technique which requires to dissolve a temperature-sensitive fluorescent tracer in the liquid fuel. The fluorescence, induced by a CW argon laser tuned at 514.5 nm, is detected over two spectral bands for which the temperature sensitivity is sufficiently different. The ratio of the fluorescence signals from both bands depends only on temperature. A preliminary study has clearly pointed out additional effects of the size polydispersion together with the fuel composition on the fluorescence signal. This study was used to derive a strategy in order to get rid of these phenomena in the present experiments. Droplet temperature profiles were recorded along the channel axis together with radial profiles at different distances from the injector. A strong increase of droplet temperature is observed immediately after injection, followed by a smoother heating at larger axial distance. Adding a little amount of a more volatile component (3-pentanone) leads to a two-stage heating. 3-pentanone evaporates first, the initial increase being followed by a plateau where it all vaporizes. At later stages, this temperature profile tends to become similar to that of pure n-decane.

In a second step, the spatial distribution of 3-pentanone vapor in the gas phase at various distances from the injector is determined by means of planar laser-induced fluorescence using a frequency-quadrupled output of a Nd:YAG laser at 266 nm. Fluorescence is recorded by an intensified CCD camera equipped with a high-pass optical filter to collect signals at wavelength larger than 320 nm. Evolution of fuel vapor concentration with distance from the injector is observed due to spray spreading and droplet evaporation. Additionally, local flow structures can be visualized and the influence of vortices on droplet trajectories can be evidenced.

1-Introduction

Liquid fuels are often used in combustion systems for propulsion of aircrafts, rockets or automobiles. Liquid fuels, generally composed of hundreds of molecules, are atomized into droplets in the combustion chamber in order to increase the exchange of heat and mass between the liquid and the pre-heated air. The most important parameters that affect the overall efficiency of the combustor and its pollutant emissions are ambient temperature, turbulence and residence time. The chemical nature of the fuel is also likely to have a significant influence on the burning efficiency and on the pollutant formation. The residence time of the fuel droplets in the combustor directly influence the size of the combustion chamber. This latest must be compatible with the droplet evaporation time, which is directed by the fuel chemical nature, ambient pressure and temperature, size and velocity distribution of the droplets, and finally by the turbulence of the air flow.

It is recognized that an adequate modeling of the gas phase will provide a good prediction for the droplet vaporization time whereas the quality of the liquid phase modeling is essential to predict accurately the auto-ignition delay.

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Among the parameters of interest, one of the less investigated one is the droplet temperature, which influences directly the local fuel air ratio. Furthermore, the knowledge of the droplet temperature is essential in modeling the droplet heating and evaporation process in the combustion chamber. The purpose of this contribution is to implement a new technique based on two-color laser-induced fluorescence to derive droplets' temperature in a spray of bicomponent droplets composed by a mixture of n-decane and 3-pentanone. These two fuels presents well differentiated volatilities and are able to mimic the evaporation of a heavy alcane associated with a more volatile component. Furthermore, 3-pentanone, when appropriately excited by an UV radiation, produces a fluorescence signal that can be interpreted in term of vapor distribution in the gas phase.

The spray is injected in a heated air tunnel, where turbulence is controlled by means of a specially designed turbulence generator. Combined measurements of the droplet temperature and of vapor distribution of the more volatile component (3-pentanone) are provided.

2-Experimental set-up

The experimental set-up consists in a vertical square air tunnel (0.8 length, 0.092 m large) where turbulence can be generated by a specially designed turbulence generator, initially developed by Santavicca et Videto [1]. Pressurized air is injected in a cylindrical enclosure (figure 1). The air is then forced through the bottom of the cylindrical chamber, pierced by 45 holes, each being 3 mm in diameter. The jets issuing from the 45 holes impact a convergent nozzle directly linked to the square test section. Different optical accesses in the test section allow implementing the different optical techniques.

With such a device, high turbulent kinetic energy can be created and the turbulence intensity can reach 30% with a good isotropy in the major part of the flow field. The air can be pre-heated up to 600 K and the flow velocity is fixed at 2 m/s. Under these conditions, the properties of the turbulent flow have been preliminarily characterized, using PIV. The turbulent kinetic energy decays as Z^{-2} , like a grid turbulence in the final phase.

An ultrasonic injector cooled by a temperature regulated water flow, is inserted within the exit of the convergent section. With such a device, the spray is injected just in the entry of the square test section (figure 1). The injection temperature of the fuel is measured by means of a thermocouple inserted in the entry of the injector. Typical droplet size distributions, measured by means of Phase Doppler Anemometry (PDA) are given in figure 2, at $Z=45$ mm, for two operating air temperature: $T=293$ K and $T=560$ K. The mean droplet diameter is $D_{10}=61.28 \mu\text{m}$ at $T_{air}=293$ K as it is $D_{10}=73.25 \mu\text{m}$ at $T_{air}=560$ K.

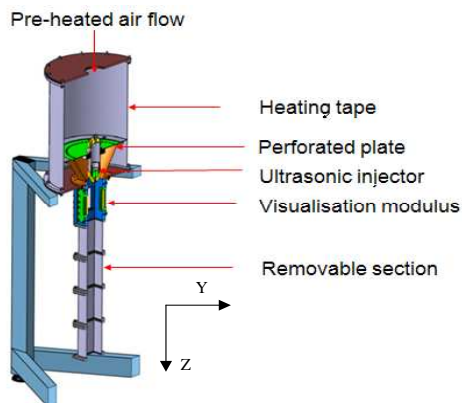


Figure 1. Scheme of the air tunnel

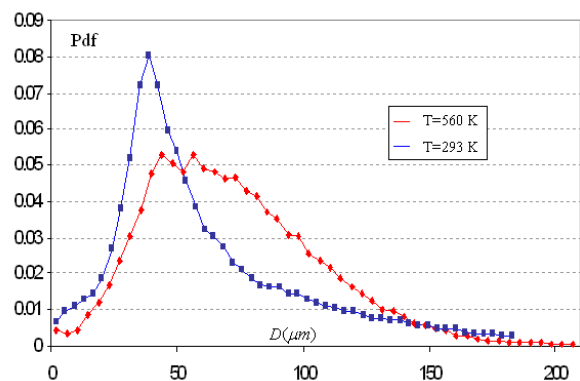


Figure 2. PDF of the droplet size distribution for the two operating air temperature at $Z=45$ mm.

3-Measurement techniques

3-1-Droplet temperature measurements

• Bases of the technique

Only an outline of the two-color LIF technique is given in this section. The fuel is seeded with a low concentration (a few mg/l) of a dye used as a fluorescent temperature sensor. A comprehensive survey of the method can be found in [2,3]. The principles of the technique remain the same whatever the tracer used, pyrromethene 597-C8 in the present study. The fluorescence of pyrromethene 597-C8 can be easily induced by the green line (514.5 nm) of the argon ion laser. The emission spectrum is broadband and extends over several hundreds of nanometers. It exhibits also

a significant dependence on the temperature. A general expression of the fluorescence intensity collected over a spectral band $[\lambda_{i1}; \lambda_{i2}]$, i denoting the spectral band, is given by:

$$I_{f,i} = K_{opt,i} K_{spec,i} I_0 V_c C e^{\frac{A_i}{T^2} + \frac{B_i}{T}} \quad (1)$$

where $K_{opt,i}$ is an optical constant taking into account the properties of the detection system (e.g. solid angle of detection and transmission of the optics), $K_{spec,i}$ is a constant depending solely on the spectroscopic properties of the fluorescent tracer in its solvent, both for the spectral band i . I_0 is the laser excitation intensity, C is the molecular tracer concentration, T is the absolute temperature, and V_c is the volume where the fluorescence photons are collected. This volume is the intersection between the laser beams, the droplet volume and the volume defined by the collecting optics. A_i and B_i are coefficients introduced empirically to account for the temperature dependence of the fluorescence emitted over the spectral band i [4]. To properly measure the temperature of a moving and potentially evaporating droplet, the influence of the parameters C , V_c and I_0 must be removed. The collection volume V_c is constantly changing as the droplet crosses the probe volume. Furthermore, the distribution of the laser intensity within the droplet depends on the relative position of this latest and also on the laser beam shape, which is influenced by the refractive and focusing effects at the droplet surface. To avoid these drawbacks, the fluorescence intensity is detected on two spectral bands, the temperature sensitivity of which is strongly different. The ratio of the fluorescence intensities collected on both optimized spectral bands is given by:

$$R_{12} = \frac{I_{f,1}}{I_{f,2}} = \frac{K_{opt,1}}{K_{opt,2}} \frac{K_{spec,1}}{K_{spec,2}} e^{\frac{A_1 - A_2}{T^2} + \frac{B_1 - B_2}{T}} \quad (2)$$

This ratio is independent on the dimensions of the probe volume. The influence of the local laser intensity and the tracer concentration are eliminated as well. The use of a single reference measurement at a known temperature allows eliminating the optical and spectroscopic constants. The position of the two detection spectral bands is optimized in order to maximize the temperature sensitivity of the fluorescence ratio R_{12} . A preliminary spectroscopic study was performed and fluorescence spectra were recorded for several n-decane/3-pentanone mixtures and various liquid temperatures. In the case of pyromethene 597-C8 dissolved in n-decane/3-pentanone mixtures, no significant effect of the composition on the fluorescence ratio and on the temperature sensitivity coefficients A_i and B_i was observed [5]. A trade-off between a high temperature sensitivity and enough detection levels leads to the selection of those spectral bands [540 nm-560 nm] and [590 nm-610 nm].

- Non linear droplet size effect

An additional effect was detected when small droplets are involved. The fluorescence ratio presents an unexpected dependence on the droplet size, under isothermal conditions. This effect is not fully understood, but is related to a global deformation of the fluorescence spectrum which could be interpreted by a population redistribution in the solute-solvent molecular system induced by a high influence excitation field [6]. Figure 3 presents the evolution of the fluorescence ratio as a function of the droplet diameter, measured for single droplets generated by a monosized droplets injector. This first set of measurements was obtained for a fluorescent tracer concentration $C=10^{-6}$ mol/l and are normalized by a reference measurement fluorescence ratio recorded in a cell. The same experiment was repeated for a dye concentration which is 10 times higher ($C=10^{-5}$ mol/l). When $C=10^{-6}$ mol/l, the fluorescence ratio presents a clear dependence on the droplet diameter for the smallest droplets size. For the biggest droplets' sizes, the fluorescence ratio collapses with the value measured in the cell, which means that the influence of the droplet size on the fluorescence ratio vanishes. When $C=10^{-5}$ mol/l, the influence of the droplet size on the fluorescence ratio is largely attenuated and the deviation with the reference measurement do not exceed 3%. Then, knowing the temperature dependence of the fluorescence ratio, the temperature of 50 μ m-diameter droplets will be underestimated by 4°C.

- Temperature calibration and effect of the mixture composition

Calibration experiments are required to capture the response of the detection system to a variation of the temperature (coefficients (A_1-A_2) and (B_1-B_2)). These experiments are performed one time for all in an agitated temperature controlled quartz-made cell for different mixtures of n-decane/3-pentanone. The fluorescence ratio R_{12} is measured under low absorption conditions while the temperature is monitored by a thermocouple.

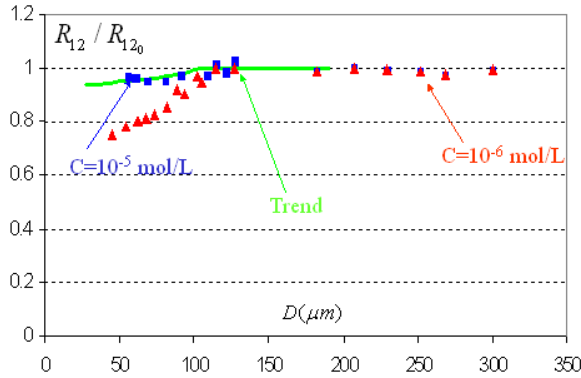


Figure 3. Evolution of the normalized fluorescence ratio as a function of the droplet size.

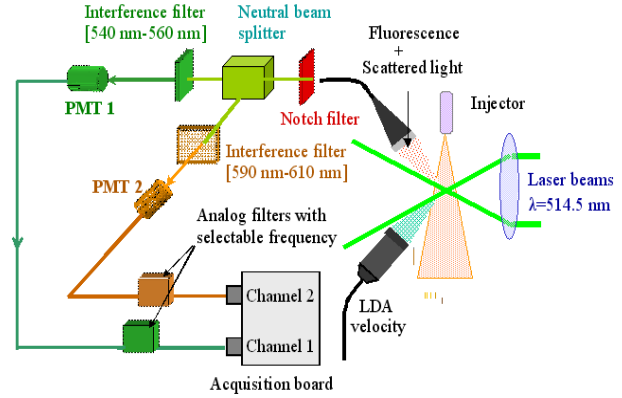


Figure 4. Sketch of the optical layout.

- **Measurement set-up and process**

Laser Doppler Anemometry beams system is used to generate the probe volume of the 2-color LIF measurement. The probe volume formed by the intersection of the laser beams is 1200 mm long and is 150 mm in diameter (transverse direction). The fluorescence signal is detected by an achromatic doublet, positioned at right angle, connected to an optical fiber acting as a pinhole. The laser light ($\lambda = 514.5$ nm) scattered by the droplets is high-pass filtered with the use of a notch filter in order to collect only the fluorescence emission. The remaining fluorescence signal is separated into the previously mentioned spectral bands by means of a set of a neutral beam-splitter and interference filters (figure 4). The optical signal detection on the selected two spectral bands is performed by means of two photomultipliers. The acquisition and sampling of the fluorescence signals are carried out by means of a computerized multi-channel acquisition board, with a sampling rate of 5 MHz.

The fluorescence signal averaged on a designated number N of droplets on the two spectral bands and the ratio is calculated following:

$$R_{12} = \frac{\sum_{i=1}^N \sum_{k=1}^p I_{fik,1}}{\sum_{i=1}^N \sum_{k=1}^p I_{fik,2}} \quad (3)$$

where i is the droplet index and k is the signal sampling index, p being the number of sample for the i^{th} droplet. Then, the measured temperature is averaged on the total liquid volume crossing the measurement volume during the measurement time.

3-2- Vapor distribution in the gas phase

PLIF experiments used a single-excitation scheme which comprises a frequency-quadrupled Nd:YAG laser generating 8 ns, 50 mJ pulses at 266 nm. The laser beam was transformed into a collimated sheet using a combination of cylindrical and spherical lenses. The two cylindrical lenses, -20 mm and 300 mm focal lengths, formed a cylindrical telescope which spread the beam into a collimated, 50 mm high, sheet. The spherical lens, 900 mm focal length, focused the sheet to a 130 μm waist. The laser sheet impacted the flow and fuel vapour fluorescence from part of the illuminated sheet was recorded by a 16-bit ICCD camera (512×512 pixels) with a 100 ns temporal gate and a 3 Hz framing rate. The ICCD camera was equipped with a $f/4.1$, $f=94$ mm, achromatic UV lens together with a high-pass spectral filter to collect fluorescence of 3-pentanone at wavelengths above 320 nm. The choice of this detection scheme aimed at increasing the signal-to-noise ratio on the fluorescence image. The camera was interfaced to a personal computer. An 80×80 mm² area of the flow was imaged by the ICCD camera, so that the spatial resolution was about 160 μm per pixel.

4- Experimental results

The experimental results are displayed for the following experimental conditions: $T_{\text{air}}=560$ K, $V_{\text{air}}=2$ m/s and $Q_{\text{fuel}}=2.7 \cdot 10^{-7}$ m³/s (liquid fuel flowrate). The fluorescent tracer is fixed at $C=10^{-5}$ mol/l to minimize the effect of the droplet size on the fluorescence ratio.

The evolution of the droplet temperature (represented as the excess temperature above injection temperature T_{inj}) along the vertical axis of the channel is presented in figure 5-and for three compositions ($Z=0, 5$ and 15% , Z being the volume fraction of 3-pentanone). Generally, regardless the composition of the fuel, a clear heating of 90°C of the droplets can be observed. The first heating phase is attenuated, when 3-pentanone is added to n-decane, since 3-pentanone is more volatile than n-decane. A zoom of figure 5-a (in 5-b) on the first measurement section, in the case of the composition $Z=15\%$, reveals a clear pseudo-plateau, localized in the middle of the heating phase. This plateau can be attributed to the high difference between the thermal and species Peclet number. In the plateau, liquid 3-pentanone is in excess at the droplet surface and vaporizes at a quasi-constant temperature. Following this vaporization phase, and due the slow diffusion process of 3-pentanone, the heating of the droplets continue because of the low volatility of n-decane. Droplet temperature profiles were also recorded on the radial axis. Close to the injection device ($Z=45$ mm), a significant temperature gradient can be observed, the droplets being 30°C hotter than in the spray centerline (figure 6). This phenomenon can be attributed to accumulation of the smallest droplets near the walls, which are likely to be heated-up very quickly, since they are more influenced by the turbulence. When the distance to the injector exit is increased, the temperature of the droplets tends to be more homogeneous due to the turbulent mixing.

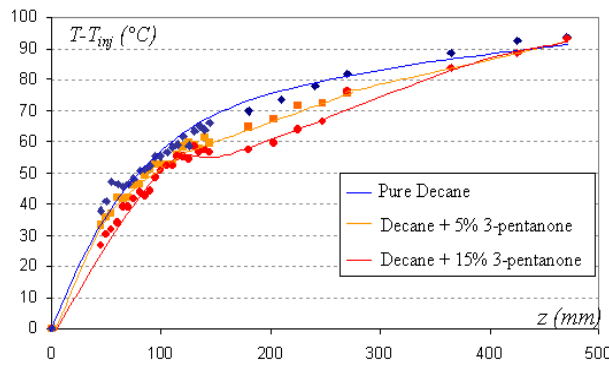


Figure 5a. Evolution of droplet temperature on the spray centerline, for 3 fuel compositions.

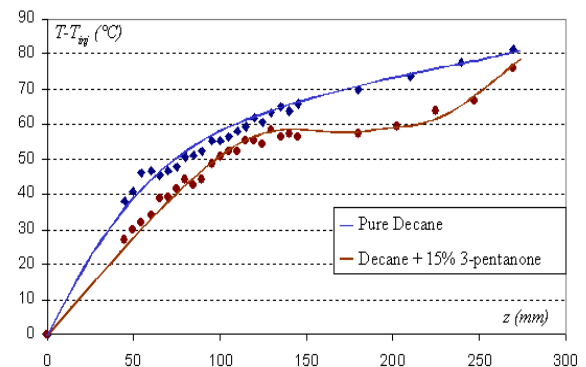


Figure 5-b. Zoom of figure 5-a on the first measurement section for pure n-decane and $Z=15\%$.

Influence of high levels of turbulence on droplet trajectory can be evidenced in figure 7. For example, the droplet highlighted with the red rectangle moves from bottom right to top left while the bulk flow direction is from top to bottom. This suggests that this droplet is influenced by a vortex which strongly modifies its initial motion (from top to bottom). In addition, fuel vapor wake is clearly seen behind the droplet, and the shape of the wake indicates the droplet trajectory. It is noticed that at the early stages of injection in the flow, the spray angle is fairly narrow ($\sim 40^\circ$). Nonetheless, 150 mm downstream from the injector, fluorescence images show that strong turbulence lead to droplets being entrained at the edges of the test rig section. Finally, as can be seen in figure 7, fluorescence from fuel vapor allows visualizing coherent flow structures at different turbulent scales.

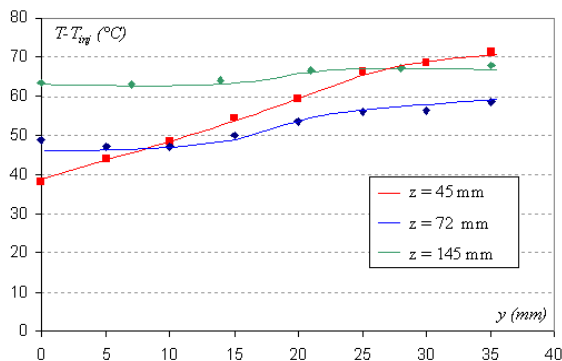


Figure 6. Transverse evolution of the spray temperature for pure n-decane.

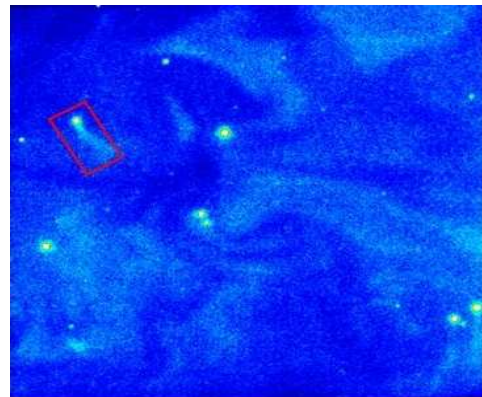


Figure 7. Influence of turbulence on droplet trajectory.

Figure 8 represents radial profiles of the molar fraction of 3-pentanone vapor at different distances from the injector. At $z=130$ mm, the spray is fully developed and the spatial distribution of 3-pentanone vapor exhibits a typical bell shape. However, it is noticed that the spray is not spread all over the section of the flowfield, although collisions of droplets with the walls are sometimes observed due to high levels of turbulence. It means that the evaporation is more intense in the center compared to the edges. This phenomenon is correlated to the highest droplet temperature observed in the edges. As distance from the injector increases, the profiles tend to become flatter, which indicates that fuel vapor spread all over the section, leading to a fairly homogeneous spatial distribution as for the droplet temperature. Nonetheless, some asymmetry is observed in the profiles, which may be attributed to fuel vapor generated close to the optical windows due to droplet collisions and splashing onto the walls. Indeed, it is noticed that molar fraction of 3-pentanone is less than 1 % in the airflow and therefore laser absorption by 3-pentanone through the flowfield is not responsible for that asymmetry and can be disregarded. At $z = 470$ mm, the local molar fraction of 3-pentanone vapor is fairly close that in the overall airflow, which indicates that little droplets still exist at that position and the liquid fuel is mainly vaporized.

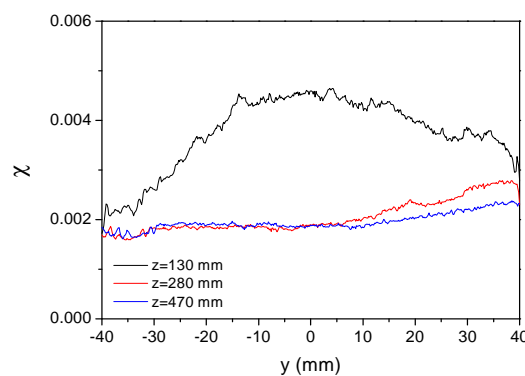


Figure 8. Radial profiles of 3-pentanone molar fraction at different distances from the injector.

Conclusions

Join measurements of bicomponent droplets temperature and fuel vapor distribution of one of the component have been successfully performed on a spray injected in a heated turbulent flowfield. The heating phase of bicomponent droplets presents a clear pseudo-plateau, resulting from the slow diffusion process of the volatile component in the other one. The behavior of fuel vapor distribution, bell-shaped in the first measurement sections and more flat as the distance from the injector is increased, is similar to what observed for the droplets temperature.

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