

## EXPERIMENTAL STUDY OF EVAPORATION OF POLYDISPERSED BI-COMPONENT DROPLETS IN A HIGHLY TURBULENT CHANNEL FLOW

Florian Moreau\*, Gerard Couteau, Moise Marchal, Rudy Bazile

\*IMFT, allée du professeur Camille Soula, 31400 Toulouse, France

email: [florian.moreau@imft.fr](mailto:florian.moreau@imft.fr) / phone : +33 5 61 28 59 36 / fax : +33 5 61 28 59 94

### ABSTRACT

The objective of this work is the understanding of the evaporation process in multi-component sprays. Typical industrial applications are aeronautical turbines or piston engines. A model experiment was designed and built to generate a heated turbulent flow in which two-component droplets are injected. The two components are octane (85%) and 3-pentanone (15%) and were chosen such that 3-pentanone liquid phase concentration could be characterized with laser techniques. The air flow is described in terms of velocity and temperature fields and the preliminary analysis of the dispersed phase is presented.

### 1. CONTEXT AND OBJECTIVES:

To reduce pollutant emissions from aeronautical combustion chambers a better understanding of injection, atomization, evaporation and mixing phenomena is required. In this study we focus on the evaporation process.

One of the first droplet-evaporation models proposed by Spalding [1] describes a single-component isolated droplet in a quiescent environment. Many authors have offered contributions to update the description level of this model. For example, Hubbard [2] accounts for variables properties of the surrounding vapour. Also, Abramson and Sirignano [3] studied convection-driven effects and introduced modified Nusselts and Sherwood numbers. Then, Chiang and Sirignano [4] accounted for the wakes of the neighbouring droplets. As for turbulence/droplets interaction, it seems to have contradictory effects: on the one hand, Birouk [5] showed that turbulence increases isolated droplet evaporation rate but on the other hand, the formation of droplet clusters, because of turbulence, may hinder the overall vapour production [6]. Finally, composition aspects have been addressed in a variety of ways such as the discrete component model [7], quite accurate but cumbersome, the Gamma Continuous Thermodynamic Model [8] needing less computational time but lacking accuracy in the case of condensation and the quadrature method of moments [9,10] which is basically a combination of the two other methods.

The focus of this study is on the interaction of a droplet spray with a highly turbulent flow. Composition aspects are addressed through the use of two-component droplets (octane/3-pentanone). Droplets diameters, velocities and 3-pentanone concentration in the liquid phase will be measured.

### 2. EXPERIMENTAL SETUP:

The experimental setup consists in a vertical channel with optical access (Fig.1). Preheated air (473K) is injected in a tank and passes through a turbulence generator before entering the channel. The generator has been adapted from a previous setup by Videto and Santavicca [11] and is made of a circular plate perforated by 45 holes of 3mm diameter and a convergent. When the air passes through the holes it creates number of jets impacting on the convergent, which generates turbulence levels much higher than classical grid turbulence: up to 25% for a mean velocity of 2m/s. In a previous study [12] the turbulence was shown to be isotropic after  $X/H = 4.5$  (Fig.2), where  $X$  is the vertical axis ( $X = 0$  corresponds to the entrance of the channel) and  $H$  the cross section of the channel. Radial profiles of the mean longitudinal velocity  $\overline{U}/U_0$  (where the operator  $\overline{\bullet}$  denotes temporal averaging and  $U_0$  is the bulk velocity) are very flat on more than 80% of the cross-section indicating that the flow is homogeneous at each section. The superimposition of  $u'/U_0$  and  $v'/U_0$  shows a good level of isotropy on a large section of the bench.

The incoming air is heated with a resistance and radial temperature profiles are found to be quite flat (Fig.3).

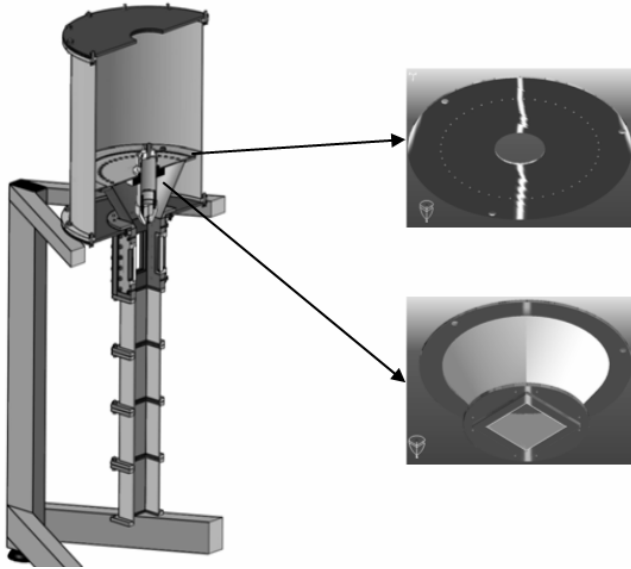


Fig.1 Experimental setup

The droplet injector is placed in the centre of the perforated plate and the tip of the nozzle is located at  $X/H = 0$ . The atomization is performed with an ultrasonic system providing a wide range of droplet diameters leading to a variety of droplet behaviours from tracers to highly inertial droplets. The droplets are a mix of octane (85%) and 3-pentanone (15%).

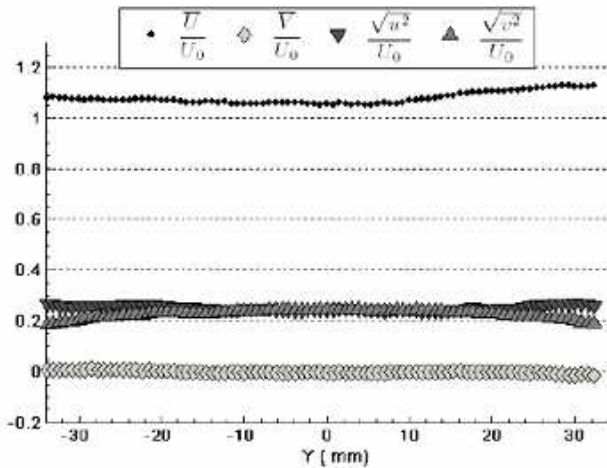


Fig.2 Velocity statistics at  $X/H=4.5$

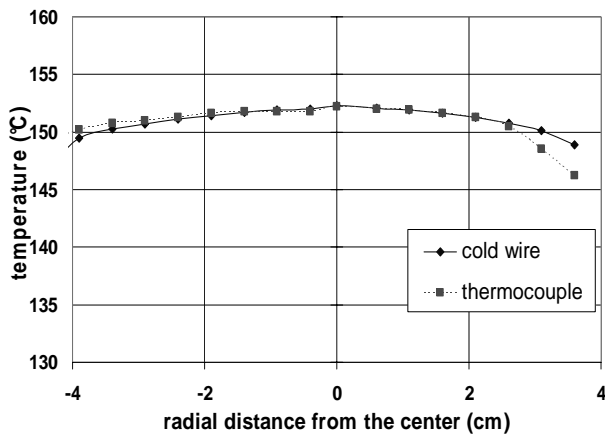


Fig.3 Radial profiles of temperature at  $X/H=1$

### 3. MEASUREMENT TECHNIQUES:

The diameter, axial and radial velocity of each droplet are determined using 2D Phase Doppler Anemometry (PDA). A continuous Argon PDA laser with 2 couples of beams (544 and 488  $\mu\text{m}$  wavelengths) was used, such that both axial and radial velocities can be measured. This technique also allows the determination of the velocity conditioned by the droplet diameter.

The concentration of 3-pentanone in the droplets is determined using Laser Induced Fluorescence (LIF) noting that the fluorescence signal of octane is negligible. The laser used for LIF experiment is a pulsed Nd:YAG laser ( $\lambda = 266\text{nm}$ ,  $\epsilon = 40\text{mJ}$ ,  $f = 10\text{Hz}$ ). The fluorescence signal is collected with a 16-bit 1024x1024 pixels intensified camera. A [300-500  $\mu\text{m}$ ] band-pass filter is used to select the fluorescence signal. The LIF signal  $S_f$  can be described using Eq.1, where  $I_0$  is the incident laser intensity,  $\phi^f$  is the quantum yield,  $\sigma$  is the absorption cross section, and  $N$  the molecular concentration of fluorescent species.

$$S_f = I_0 \phi^f \sigma e^{-\sigma \int N(x).dx} N(x) \quad (1)$$

Assuming that  $e^{-\sigma \int N(x).dx} \approx 1$  for the spray, which corresponds to Beer-Lambert absorption, all the other terms can be determined by calibration so that  $S_f$  depends linearly on  $N$ . This allows the determination of the mass fraction of 3-pentanone in the liquid phase.

### 4. RESULTS:

#### 4.1. Initial conditions of droplet injection (PDA):

The first measurements to characterize the initial conditions of the spray were performed without preheating the airflow. The longitudinal velocities conditioned by the diameter along the channel axis (Fig.4) reveal a recirculation zone after the injector. As expected, the largest droplets, which are more inertial, are less influenced than the smallest ones. Incidentally, the middle-size class is representative of the whole droplets behaviour. The diameter probability density function (pdf) on the X axis (Fig.5) shows an evolution from small to large diameters. This is conjectured to be due to both coalescence and small particles that are pushed away from the axis by the turbulence.

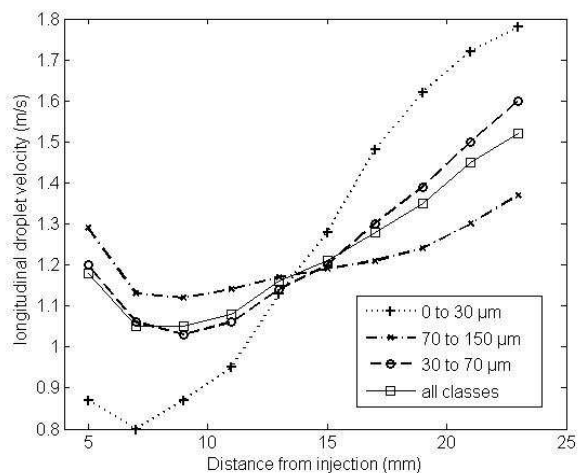


Fig.4 Longitudinal droplet velocity on the axis for several diameters classes

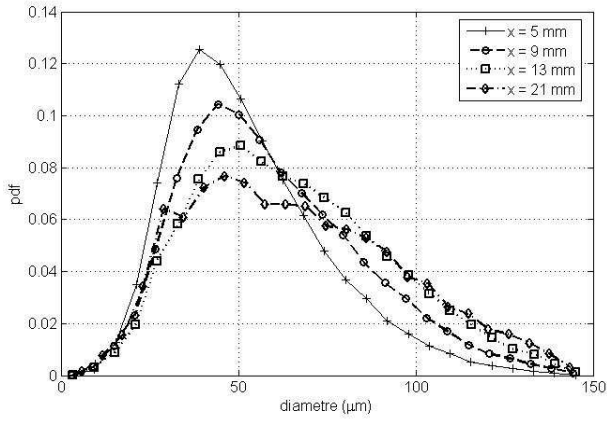


Fig.5 Diameter pdf at several axial location from injection

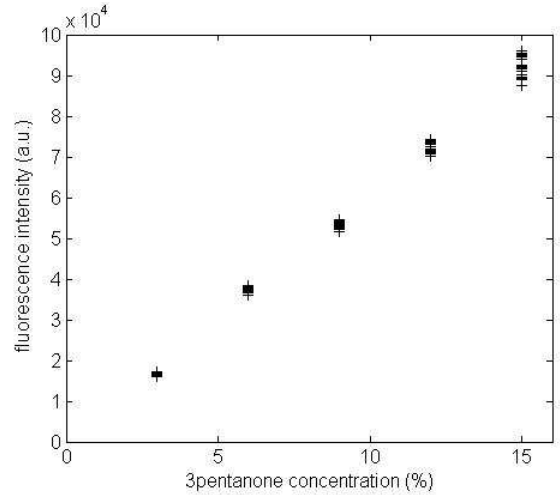


Fig.7 Fluorescence intensity evolution with 3-pentanone volume fraction at several temperatures

#### 4.2. Liquid phase characterization (LIF):

LIF signal is known to be potentially temperature dependent. During the droplet evaporation, temperature will increase and 3-pentanone concentration will change inside the droplet. Validations were conducted to assess that the effect of temperature variations have a negligible impact on the measurement of the composition. A small quartz tank was filled with liquid at several concentrations of 3-pentanone (from 3% to 15% in mass) and the LIF signal was measured for several temperatures, ranging from 30°C to 60°C (Fig.6 and 7). For a given mass fraction, the maximum relative difference is less than 5%.

The conclusion of this benchmark is twofold; first the LIF signal is marginally perturbed by temperature variations yielding a good precision of the measure. Then the relation between fluorescence intensity and 3-pentanone concentration is linear.

#### 5. PERSPECTIVES

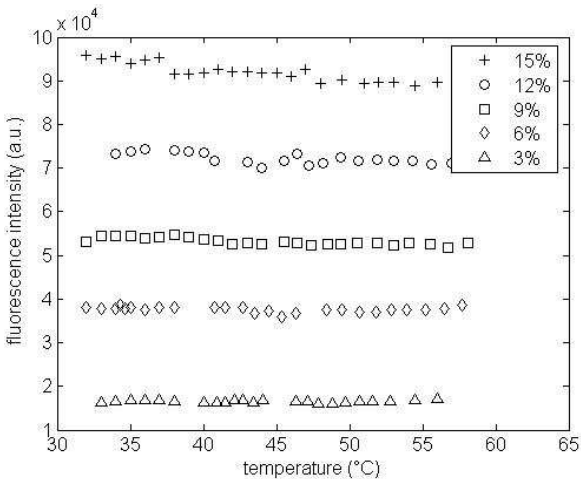


Fig.6 Influence of temperature and 3-pentanone mass fraction on fluorescence intensity

- As already been explained, the LIF signal depends on the amount of fluorescent molecules inside the excited liquid volume. In the case of a mist, because of liquid phase dispersion in the channel, 3-pentanone volume fraction is at least ten times lower than in the tank. Therefore an alternative calibration method developed by Ferrand et al [13] will be used in the present experiment for the spray calibration. This method is based on a LIF/PDA coupling and on liquid mass conservation, without vaporization.
- First spray characterizations have been carried out using LIF. In this experiment liquid mass loading is 4% and the area investigated is the first section between X=60 and X=160mm. The results show a wide range of behaviours of dispersion in the turbulent flow (Fig.8a and 8b). Droplets can be completely dispersed or grouped advecting vapour.

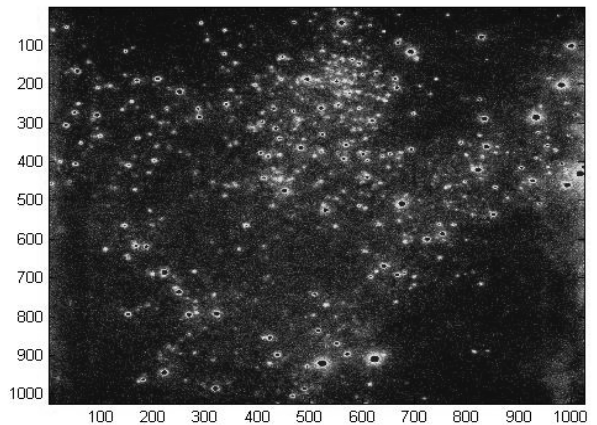


Fig.8a

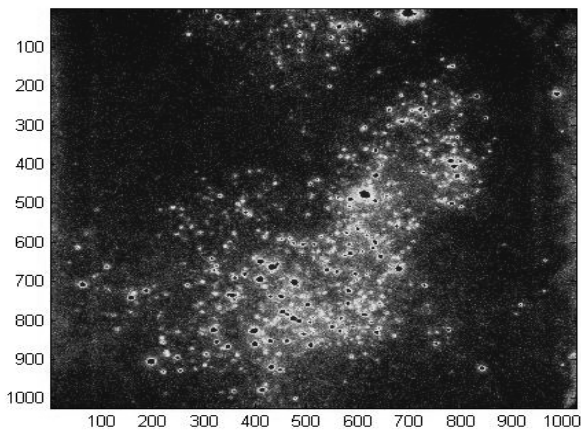


Fig.8b

Instantaneous concentration fields of 3-pentanone

- In order to find homogenization speed and if evaporation occurs individually or by group, droplet spotting algorithms will be used.
- Mean and fluctuant statistics on 3-pentanone liquid phase will be calculated.
- Droplets size and velocities will be obtained up to droplets' complete evaporation
- After complete droplets' evaporation, vapour structure evolution will be investigated using coupled PIV fluorescence techniques.

#### ACKNOWLEDGMENT

The authors would like to thank S. Cazin and E. Cid for their support on the Laser techniques as well as all the people at the mechanical workshop.

#### NOMENCLATURE

Symbol	Quantity	SI Unit
H	Channel cross section	mm
$I_0$	Incident laser intensity	a.u.
N	Molecular concentration	molecule/m <sup>3</sup>
$S_f$	Fluorescence signal	a.u.
U	Longitudinal velocity	m/s
$u'$	Longitudinal velocity fluctuation	m/s
$\bar{U}$	Mean longitudinal velocity	m/s
$U_0$	Bulk velocity	m/s
V	Radial velocity	m/s
$v'$	Radial velocity fluctuation	m/s
$\bar{V}$	Mean radial velocity	m/s
X	Longitudinal axis	mm

Y	Radial axis	mm
$\epsilon$	Laser energy	mJ
$\phi^f$	Quantum yield	
$\lambda$	Laser wavelength	Nm
$\sigma$	Absorption cross section	cm <sup>2</sup> /molecule

#### REFERENCES

- [1] D.B. Spalding. Combustion of fuel particles, *Fuel*, vol. 30, 1951.
- [2] G.L. Hubbard, V.E. Denny, and A.F. Mills. Droplet evaporation: effects of transient and variable properties. *International Journal of Heat and Mass Transfert*, vol. 18, pp.1003-1008, 1975.
- [3] B. Abramzon and W.A. Sirignano. Droplet vaporization model for spray combustion calculations. *Int. J. Heat and Mass Transfer*, vol. 32, pp. 1605-1618, 1989.
- [4] C.H. Chiang and W.A. Sirignano. Axisymmetric calculation of three droplets interactions. *Atomization and sprays*, vol. 3, pp. 91-107, 1993.
- [5] M. Birouk, C. Chauveau, B. Sarh, A. Quilgars, and I. Gökalp. Turbulence effects on the vaporization of monocomponent single droplets. *Combust. Science and Technology*, 1996.
- [6] J. Sornek, R. Dobashi, and T. Hirano. Effect of turbulence on vaporization, mixing, and combustion of liquid.fuel sprays. *Combustion and Flame*, 2000.
- [7] Sirignano, W. A., Fluid Dynamics and Transport of Droplets and Sprays, Cambridge Univ. Pr. (1999).
- [8] Harstadt, K. G., Le Clercq, P. C. and Bellan, J., Statistical Model of Multicomponent-fuel Drop Evaporation for Many-Droplet Liquidgas Flow Simulations, *AIAA Journal*, vol. 41, pp. 1858-1874, 2003.
- [9] McGraw, R., Description of Aerosol Dynamics by the Quadrature Method of Moments, *Aerosol Science and Technology*, vol. 27, pp 255-265, 1997.
- [10] Marchisio, D. L. and Fox, R. O., Solution of Population Balance Equations Using the Direct Quadrature Method of Moments, *Journal of Aerosol Science*, vol. 36, pp 43-73, 2005.
- [11] Videto and Santavicca, A turbulent flow system for studying turbulent combustion processes. *Combustion Science and Technology*, 1991.
- [12] M. Cochet, Evaporation de gouttelettes polydispersées dans un écoulement de canal fortement turbulent. Analyse de la formation du mélange diphasique par imagerie de fluorescence, Ph.D. thesis, INPT, Toulouse, France, 2008.
- [13] V. Ferrand, R. Bazile, J. Boree. Measurements of concentration per size class in a dense polydispersed jet using planar laser-induced fluorescence and phase Doppler techniques, *Experiments in Fluids*, vol. 31, pp. 597-607, 2001.