Investigation of Burning Sprays Applying GSI Out-of-Focus Technique

Calabria R., Casaburi A., Massoli P.

Istituto Motori - CNR, Via Marconi 8, 80125 Napoli, Italy

The paper discusses the application of Generalized Scattering Imaging out-of-focus technique to burning sprays. Droplets size distributions in isothermal, evaporating and burning sprays were inferred by measuring intensity oscillation spacing in droplet "string" images at a scattering angle of 60°. No difficulties were caused by gaseous density gradients and by laser light scattering and thermal emission from soot particles. In all experiments string droplets images were clearly defined and size function distributions easy to recognize. This permitted a detailed characterization of burning sprays.

1. Introduction

The measure of diameter and refractive index of droplets represents a powerful tool in the study of burning sprays, being droplets in combustion characterized by marked variations of composition and size. However, the use of laser techniques in burning sprays is complicated by the presence of strong temperature and, hence, of refractive index gradients around droplets. Depending on the burner configuration, the addition of swirl is used to reinforce the structure of the burning spray in a system of overlapped flame shells. The influence of the misalignment of the incident laser beam and of the diffused radiation due to density gradients inside flames can be recovered by using appropriate lenses systems. Thus, a good signal to noise ratio is typically achieved in flames when optical techniques exploiting 1-D or line-of-sight configuration (elastic light scattering, extinction, etc.) are used. The effect of distortion of the visual field is, on the contrary, extremely relevant in case of imaging techniques. In particular, no detailed analysis of the difficulties experienced during application of high definition imaging techniques to burning droplets is usually discussed in literature. Aim of the paper is to discuss the experimental feasibility of the *Generalised Scattering Imaging*, GSI, out-of-focus technique [1, 2], to study hydrocarbon fuel droplets in combustion regime.

2. *Generalised Scattering Imaging*, GSI, out of focus technique

The technique is based on the analysis of the scattered field that is imaged inside the defocused picture of droplets. In out of focus conditions the droplet contours are not well defined (as observed in in-focus imaging techniques) and the image formed inside each defocused droplet picture is the "image" of the electromagnetic field scattered by the droplet itself [3]. The scattering angular pattern of a droplet is characterized by intensity oscillations. Thus, such an oscillatory behavior is imaged in out of focus images of droplets (Fig.1). The scattered field contains all information on the scatterers [4] and, hence, from the analysis of out-of-focus images, the properties of each droplet are inferred. In particular the technique is based on the dependence of the angular spacing of oscillations on the droplet diameter [4].

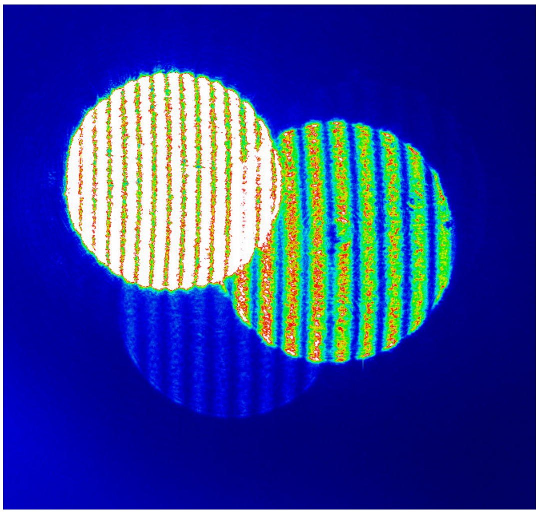

Fig.1 GSI out-of-focus images of tetradecane droplets

The utilization of out-of-focus images for the sizing of homogeneous droplets was firstly demonstrated in [3]. In such a paper, the diameters of droplets were inferred by measuring the number of oscillations per degree inside each out of focus droplet images.

GSI technique represents the generalization of the out-of-focus sizing techniques proposed in [3] to non-homogenous droplets. The generalization consists in the definition of a new experimental approach, still based on out of focus images, allowing the sizing of homogenous and inhomogeneous droplets. After an accurate theoretical analysis of the scattering patterns of homogeneous and inhomogeneous droplets it was found that at a scattering angle ϑ=60°, the influence of the complex refractive index, *m*, (in case of homogeneous droplets) and of its distribution inside the droplet, *m(r)*, (in case of inhomogeneous droplets) on the angular spacing of oscillations is negligible [1,5]. More, it was found that the droplet diameter is related to the intensity oscillation spacing, $\Delta\vartheta$, by means the simple relation:

$$\Delta\vartheta\ (\vartheta, m(r), \mathrm{D}) = 1.129\ (180° / \alpha) \qquad \text{at } \vartheta = 60° \qquad (1)$$

independently of droplets refractive index, that means independently of droplets composition and temperature. $\alpha = \pi D/\lambda$ is the scattering size parameter and λ is the light wavelength.
After some simple manipulation the previous relation can be transformed in a more direct one:

$$\mathrm{D} = 1.129\ (\lambda / \Delta\vartheta) \qquad \text{at } \vartheta = 60° \qquad (2)$$

where D and λ are expressed in micron and $\Delta\vartheta$ in radians. In *GSI* out of focus technique, the size of droplets is inferred by measuring the angular spacing of intensity oscillations of the scattered light in defocused droplet images (Fig.1) and by using relations (1) or (2) [2,4,6].
GSI technique is particularly suitable to study evaporating droplets in non-stationary regime and, in general, when variations of refractive index are expected [7]. In this paper we will discuss the potentiality of the method when applied to burning droplets. Details on the more recent developments of the technique can be found in [8].

2. Experimental set-up

Figure 2 shows the layout of the experimental set-up used to study burning droplets. It consists in a pulsed Nd-Yag laser as light source, a vibrating orifice generator to produce small sprays, a heating system to heat and ignite droplets and a CCD imaging system to capture droplets images.
The second harmonic of the Nd-Yag laser, λ=532 nm, was used in the tests. The laser operated at a repetition rate of 10 Hz. The pulses duration was 10 ns and it was short enough to "freeze" images of droplets. A cylindrical lens focused the laser beam in a sheet 55 μm thin. The height of the light beam was not manipulated and hence the sheet was 10 mm height.

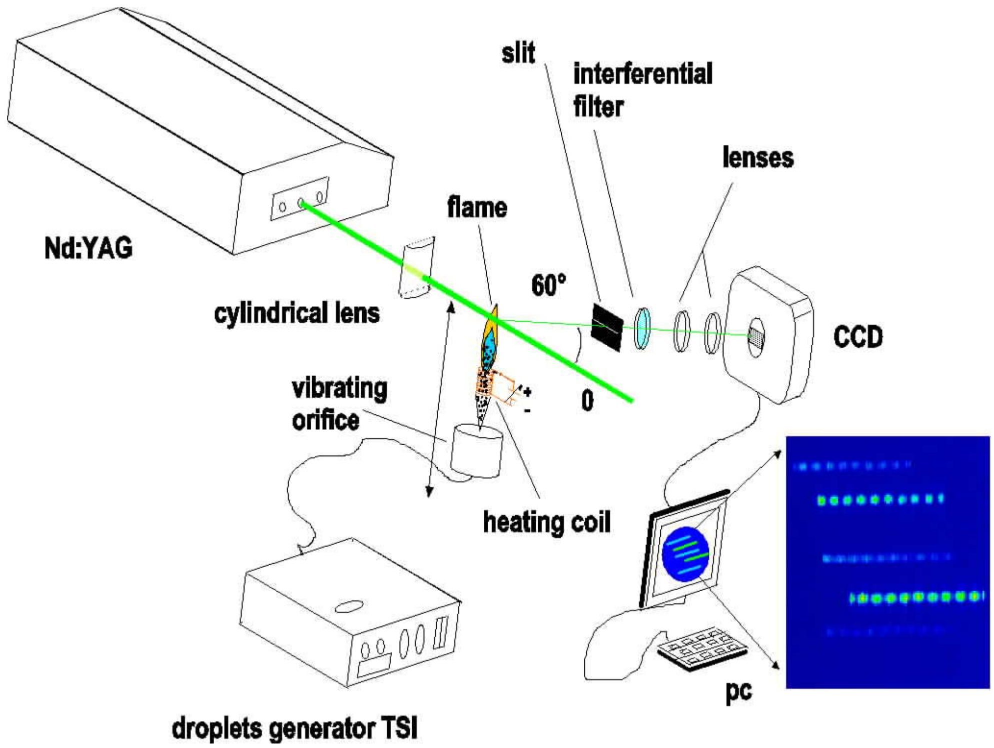

Fig. 2 Experimental set-up.

A vibrating orifice system was used to produce the sprays. By properly setting the frequency of the oscillator, arrays of calibrated droplets of known size were generated. In the combustion tests the frequency was set outside the range of standard operation in order to produce sprays with large size distributions. To generate droplets between 40 μm to 200 μm two different orifices of 20 μm and 35 μm were used in the tests. The imaging system captured images of droplets passing through the light sheet in the probe volume. The CCD (1024x1024 pixels square array) is mounted on a linear translation stage thus permitting to catch in-focus and out-of-focus droplets images. The out of focus distance was 55 mm in all experiments. The CCD imaged a 40 mm x 40 mm squared area. The measure area was 40 mm long and 10 mm height being determined by the intersection of the imaged area and the laser beam.
The detection optics is placed at a scattering angle of 60° according to the previous theoretical discussion. In order to increase the counting rate and the signal to noise ratio, a slit of 250 μm was horizontally placed in front of the collecting optics. Using this configuration, the circular image of each droplet is reduced to a string (Fig. 3) thus permitting the study of

denser sprays [9,6,8]. In fact, images of droplets that are superimposed in the standard “all image” configuration (Fig.1), appear as a collection of separate strings by using this optical configuration.
In all experiments, isothermal, high temperature and combustion, the droplets diameters were inferred by measuring the angular spacing of intensity oscillations of the scattered light in defocused droplet strings (Fig.3) and by using the unique relations (1) or (2).

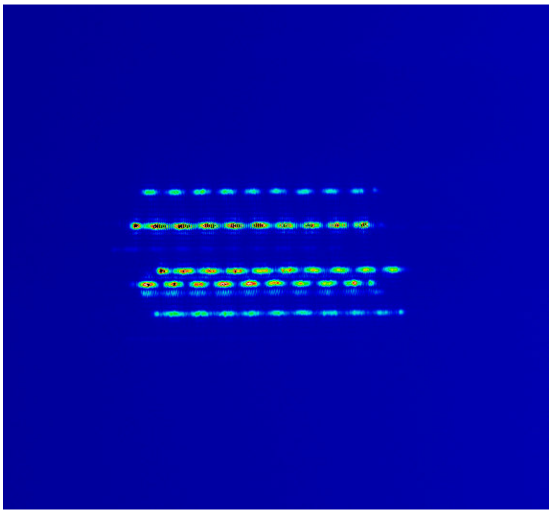

Fig. 3 GSI out of focus technique image of grouped isopropyl alcohol droplets in isothermal condition. Every string in the image corresponds to a single droplet.

3. Characterisation of burning spray

The aim of the paper is to examine the effect of the presence of a flame in the application of GSI out-of-focus technique. In order to analyze the difficulties due to gaseous thermal gradients, two different heating/ignition systems were utilized. To study the influence of particulate matter around burning droplet, fuels with different soot tendency were tested. In the experiments we are discussing, isopropyl alcohol, hexane, and octane were used. The alcohol flames were almost completely blue, with exclusion of a small spot in the tip of the flame tail, this meaning absence of soot. On the contrary, flames from hexane and octane were characterized by large luminous yellow zone, rich in soot, especially in the tail.

3.1. Isothermals spray

Two different series of experiments were carried out. In a first group of tests, the vibrating orifice operated to generate an array of calibrated droplets of isopropyl alcohol. This set of experiments was used to test the experimental system and also to calibrate it. The droplets diameters were measured 54 mm above the generator head in isothermal conditions. To avoid droplets coalescence a dispersion air flux of 1500 cc/min was used. Figure 4 shows the size distribution of droplets measured in such a condition when a 20 μm orifice was used.

3.2. Evaporating and burning sprays

In the second group of tests, both calibrated array and sprays with large droplet size distributions were characterized in evaporating and burning regimes. For comparison size distributions were measured also in isothermal conditions. A resistive coil or a micro flame was used to heat and ignite droplets. Droplets diameters were measured at different locations in the spray to study droplets evaporation.

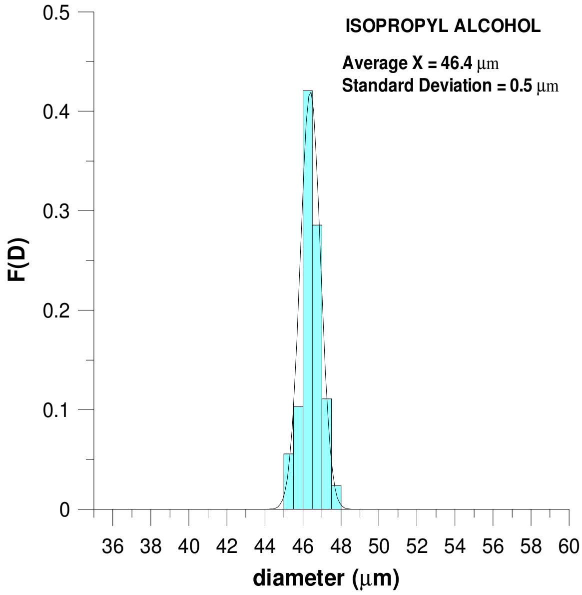

Fig. 4 Size distribution of calibrated isopropyl alcohol droplets.

Figures 5 reports the results of tests carried out on arrays of calibrate droplets of octane. The size measurements were performed both in combustion and isothermal conditions at the same spatial location, 78 mm above the droplet generator head. The red histogram is relative to measurement in flame while the blue one corresponds to diameter measurements at room temperature. The size distribution of droplets at ambient temperature is very peaked. A gaussian fit of the distribution gives a mean diameter of 45.1 µm ± 0.7 µm. A flame from a micro solder fuelled with propane was applied sideways to the calibrated droplet array at 43 mm from the generator head.

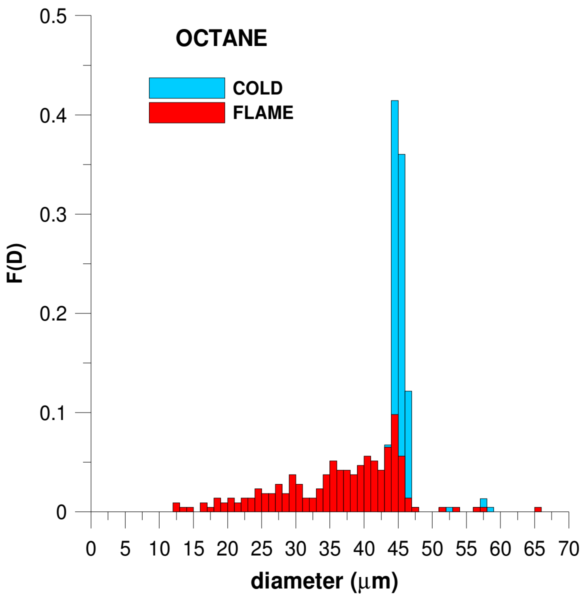

Fig. 5 Normalized diameter distribution functions of calibrated octane droplets measured at room temperature and flame conditions.

The comparison between the size distribution determined at cold and high temperature conditions shows the marked size reduction of droplets due to evaporation and combustion processes. The size of droplets in flame shows a wide distribution that ranges from the typical size of cold droplets, about 45 µm, down to 10 µm. Such a spreading has to be correlated to the ignition system. In fact, due to the lateral location of the flame, ignition of the spray was not uniform and droplets in different zone of the spray underwent different thermal histories. In addition, the spray flame was not stable showing a marked flickering. Due to both the previous effects we expect that part of droplets did not burn and only marginally felt the effect of high flame temperature. As a result their diameter was almost unvaried respect to the cold measurements. Finally, it has to be taken into account that due to the laser beam height, droplets at different locations along the flame are simultaneously captured in every spray image. Thus the data sample is not homogeneous in the sense that corresponds to droplets with different elapsed (heating/ evaporation/ combustion) times.

In a second series of test, arrays of calibrated droplets of hexane were examined. The size distribution was a little bit larger respect to octane tests and peaked at a smaller mean diameter: 38.7 µm ± 1.2 µm (Fig.6). The micro solder flame was used to ignite the spray. The size measurements were performed both in combustion and isothermal conditions at the same spatial location used for octane, 78 mm above the droplet generator head, whereas the ignition micro solder was located at 50 mm respect to the generator head. As a result, hexane droplets experienced a shorter heating/burning time respect to octane droplets and, hence, the size distribution of hexane droplets at high temperature shows a limited broadening toward small diameter respect to the case of octane (Fig.6).

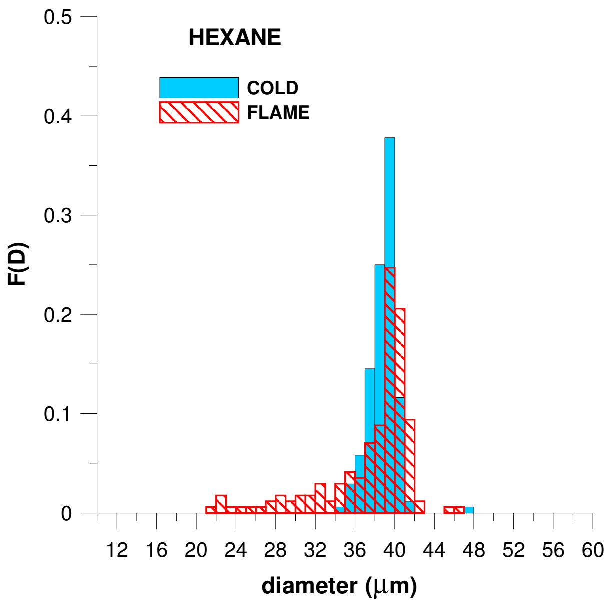

Fig. 6 Normalized diameter distribution functions of calibrated hexane droplets measured at room temperature and flame conditions.

Interesting enough, the high temperature diameter distribution shows a slight broadening also toward larger diameter. This finding is due to droplets that marginally interacted with the flame, thus experiencing a volumetric expansion before evaporation took place. The average thermal expansion coefficient of hexane at normal pressure is of the order of $1.4 \cdot 10^{-3}$ K^{-1} [10]. Droplets were produced at 20 °C. Since hexane boiling point is 68 °C, it is reasonable to expect a maximum variation of droplet temperature of about 40 °C. Thus, the maximum expected volumetric expansion of hexane droplets is ≈ 6%. For droplets of 40 µm this corresponds to a diameter increase of about 0.8 µm, in good agreement with the experimental results.

In a further series of experiments we experienced non-calibrated sprays of isopropyl alcohol characterized by very large diameter distribution functions centred at great values. Differently from the previous tests, the spray was injected inside a resistive coil electrically heated. The coil, 24 mm long, was placed between the head of the droplet generator and the laser beam. The applied voltage controlled the temperature inside the coil. Ignition was obtained when the temperature inside the coil overcame the autoigniton temperature of 2-propanol (T_{ai}= 425 °C). The operation of the coil to a lower temperature (by using a reduced voltage) permitted to study sprays in evaporating conditions at high temperature but in absence of combustion. Thus, sprays of isopropyl alcohol were characterized at room temperature, in evaporating and burning regimes. Figure 7 compares the size distributions measured in the three regimes (cold, evaporating and burning).

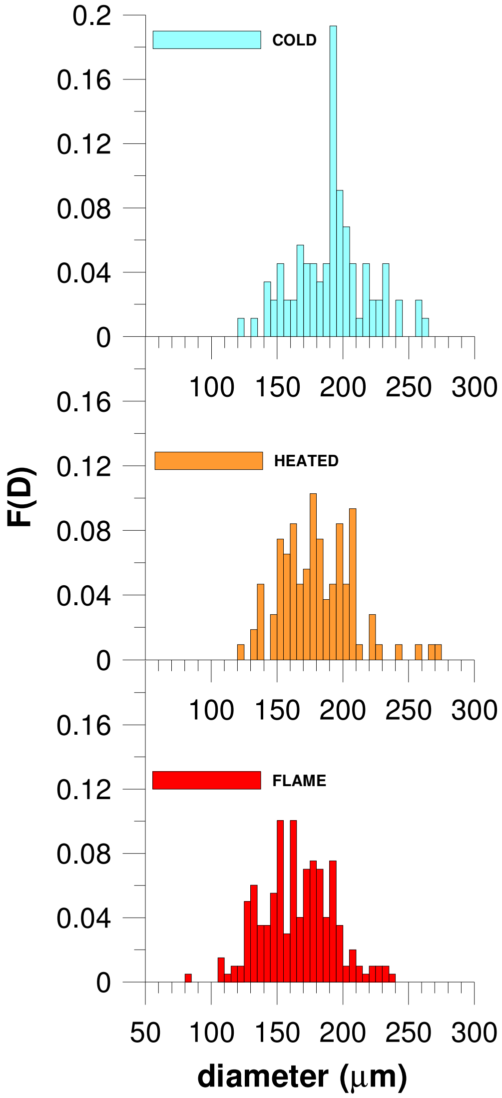

Fig. 7 Normalized diameter distribution functions of isopropyl alcohol sprays measured at different thermal regimes.

A clear shift and flattening of size distributions at high temperature is observed, with the distribution of droplets in evaporating regime intermediate between the distributions corresponding to cold and burning regimes. However, the structure of the function distribution remains almost the same. This means that, differently from the previous cases with lateral ignition, droplets experienced similar thermal vicissitude. When fitted with a gaussian fit the mean values are 191.4 μm, 180.8 μm and 165.7 μm for isothermal, evaporating and burning conditions, respectively. Measurements were performed in the same spatial location. Supposing a D^2 law, the results indicate that droplets burning rate is about twice the evaporation rate, in good agreement with literature [11].

5. Conclusions

The set of experiments discussed in the paper shows that the GSI-out of focus technique is able to work in flame. The choice of a scattering angle of ϑ=60° permitted to measure droplets size with no regard to their refractive index. The distortion of images due to the presence of thermal gradients in the gaseous phase did not sensibly affect the quality of droplets strip images. Measurements in flame were performed at different positions along burning sprays. Two different zones of the flames were investigated: the blue region poor in soot and the luminous yellow plume rich in soot. In the tested condition, laser light scattering and light thermal emission from soot particles caused no particular troubles in the recognition of droplets string images. On the contrary, also in sooting flames, the technique conserved a high sensitivity. The experiments discussed in the paper evidence that GSI technique permits to study in detail the complex phenomenology underwent by droplets in evaporating and burning sprays. It is worthwhile to remark that this is possible due to the peculiar features of the GSI technique that permits to perform sizing measurements independently of droplets refractive index.

6. References

[1] Massoli P and Calabria R 1999 *15th Conf. on Liquid Atomization and Spray Systems, ILASS-Europe, Toulouse, July 5-7*

[2] Calabria R and Massoli P 2000 *10th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, paper 10.4, Lisbon, July 10-13*

[3] Ragucci R, Cavaliere A and Massoli P 1990 *Part. Part. Syst. Charact.* **7** 221-225

[4] Kerker M 1969 *The Scattering of Light and Other Electromagnetic Radiation* (New York: Academic)

[5] Calabria R and Massoli P 2001 *17th Conf. on Liquid Atomization and Spray Systems, ILASS-Europe, Zurich, September 2-6*

[6] Calabria R and Massoli P 2002 *11th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, paper 10.4, Lisbon, July 8-11*

[7] Massoli P 1998 *Appl. Opt.* **37**, 3227-3235

[8] Calabria R, Casaburi A and Massoli P *Improved GSI Out-of-Focus Technique for Application to Dense Sprays and PIV Measurements, 9th Int. Conf. on Liquid Atomization and Spray Systems - ICLASS 2003, Sorrento, Italy, July 13-17*

[9] Krüger S and Grünefeld G 2001 *17th Conf. on Liquid Atomization and Spray Systems, ILASS-Europe, Zurich, September 2-6*

[10] Heremans K and Smeller L. 1998 *Biochim. Biophys. Acta* **1386** 353-370

[11] Chigier NA 1981 Energy, Combustion and Environment (New York: McGraw-Hill)