2D soot volume fraction measurements in a ethylene diffusion flame by two-dimensional two-color laser-induced incandescence technique

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Laser-induced incandescence technique (LII) is a promising tool that allows temporally and spatially resolved characterization of soot in terms of soot volume fraction and particle size. At high laser fluences, soot particles absorb the laser light, reaching, during the laser pulse, temperatures well above the flame temperature, and emitting a thermal radiation with peculiar features. In order to describe the process, several physical phenomena have to be considered, such as: the absorption of laser energy, the heat transfer to the surrounding gases by conduction, the energy spent in vaporisation, the increase of internal energy, and the energy loss by blackbody radiation (Melton (1984)). According to this model the maximum incandescence signal is proportional to the soot volume fraction, and the subsequent temporal decay depends on the particle size (Melton (1997)). In order to have absolute measurements, a calibration procedure is required. This is mainly carried out by comparison with other techniques (Vander Wal et al. (1996), (1998), such as, for example, extinction. LII technique can be applied for point measurements, in which it exhibits high spatial resolution and sensitivity and for 2D visualization. A two color version of LII has been developed (Smallwood), which in principle allows to avoid comparison with measurements performed with independent techniques. At the moment, however, literature about this particular aspect remains rather poor. When extended to 2D case, it potentially allows to achieve in a single shot the whole soot volume fraction distribution. Although many works on LII are reported in literature, both on theoretical modeling (Michelsen) and on the experimental approach (Smallwood), many efforts are still required for an accurate description of the physical and chemical processes involved in nanosecond heating of soot particles. Several discrepancies and uncertainties still prevent a straightforward interpretation of the overall phenomenon. Soot refractive index, maximum soot temperature, LII signal dependence on laser irradiance, are just a few meaningful points of concern.

In this work we deeply investigate some aspects regarding the maximum temperature and particular experimental aspects. A first analysis is employed on punctual LII measurements. The laser beam was accurately controlled both in shape and fluence, being the structure of the probe volume a key point. The detection system efficiency (collection optics, monochromator and photomultiplier) was accurately determined with a calibrated lamp. Soot maximum temperature versus laser fluence was determined in order to find the best experimental conditions. The punctual LII results were compared with classical extinction measurements. Excellent agreement demonstrated the capability of the technique. An extension of this technique to the 2-dimensional case is also presented. In this case too, a deep investigation of the laser light distribution in the probe volume is considered. Moreover, the ratio of two images of the flame collected at two wavelengths allows to investigate how the temperature changes across the flame. The shape of LII distribution gives and idea about fv mapping. Measurements were taken in a laminar diffusion flame of ethylene.

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Two-color LII technique

The Laser-Induced incandescence (LII) technique is a powerful soot diagnostics to measure both soot temperature and volume fraction (fv). We know that, the intensity of LII signals peak, taken within a certain range of laser fluences, is proportional to fv. Actual soot concentration measurements require a calibration procedure of LII signals in a flame of known soot concentration. To overcome this, here we propose a two-color version of the LII technique, which is just an extension of the well known two-color emission technique. The key point is the fact that, within a certain laser fluence range, the maximum temperature is independent on the particle size and is always close to the soot vaporization temperature. By working in this temperature conditions without inducing substantial mass losses during the laser pulse, accurate spatially-resolved soot concentration measurements can be carried out.

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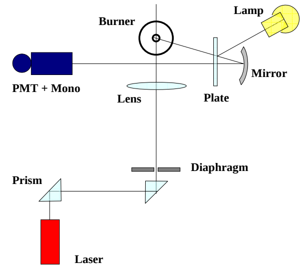
Point LII measurements



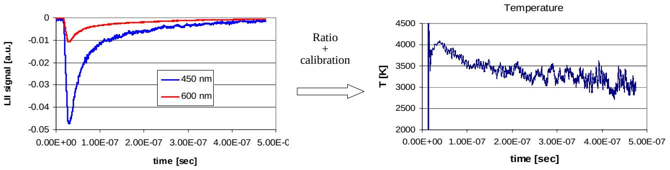
- 1064 nm excitation
- achromatic LII detection
- probe volume control
- calibration
- extinction (not shown)

Laser cross beam

+10 mm **Image plane** **-5 mm**

A webcam is used to investigate laser cross beam in the probe volume. We report single shot digital images of the cross beam taken in the image plane and away from this.

LII signals at two different wavelengths (450 nm and 600 nm) are collected. Typical LII curves vs time are reported in the following (averaged on 500 samples). By taking the ratio between them and by means of a proper calibration procedure with a calibrated source, both the temperature decay and the soot volume fraction can be obtained. In fact, the maximum LII signal, which is the signal at the vaporization temperature (Prompt LII), is proportional to the soot volume fraction (Melton). A typical example of the soot temperature decay is reported (power density: 0.4 $*10^8$ W/cm^2.

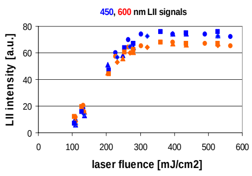


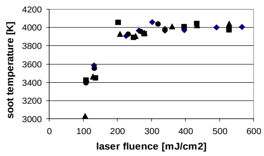
A statistical analysis was carried out to determine the best procedure for prompt LII measurements. The signal was integrated over a gate with the following features

- wide enough to increase signal to noise ratio (SNR)
- to reduce the influence of vaporisation (fv reduction)

Our tests show that a 4 nsec wide gate around LII signal peak was a good compromise

Study of LII signal dependence from laser fluence

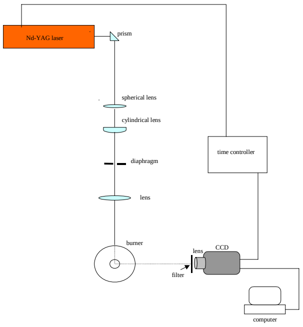




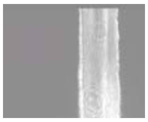
- Prompt LII signals, and consequently soot temperature, are quite constant in the range 300-600 mJ/cm^2 (saturation region)
- This finding holds in every region of the flame (for any soot load, particle and aggregates size)

We choose to work in the range 300-350 mJ/cm^2. In fact, it ensures the LII intensity to be weakly dependent on the laser intensity and a limited impact of vaporization

2D LII measurements



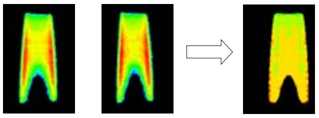
Laser sheet



The same webcam used for the point measurements is utilised to obtain the light distribution of the laser sheet in the probe volume. Because of the reduced dimension of the webcam sensor (2.6 mm in the vertical direction), only a part of the imagine of the slit is represented. A strip of 700 um of laser sheet is obtained with very sharp edges. The fringes and the circles are due to the filters (not used during LII measurements). An average fluence of 480 mJ/cm2 was estimated.

A fast digital CCD camera is used with a 3 nsec gate. Images of part of the flame are collected with interferential filters (500 nm Δλ = 10 nm, and 647 nm Δλ = 9 nm). Particular care was taken to synchronise the gate with the peak of the LII signal. However, two different problems occur: the jitter of the electronic synchronization (laser Q-switch driving pulse and the actual arrival of the laser at the flame location), and the flame flickering. An average measurement was implemented.

- for 500 nm, 20 individual images, each consisting of the accumulation of 15 shots
- for 647 nm, 10 images of 30 shots.

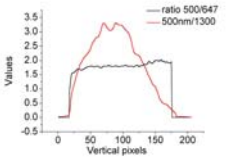


500 nm 647 nm ratio

The image of the ratio highlights that an almost uniform value is obtained indicating that the peak temperature of soot is constant in all region of the flame in spite of the strong variation in soot concentration and size of primary particles.

In a wide central part of the flame the ratio has a mean value of $R_{500/647}$=1,809 with a standard deviation σ=0.048

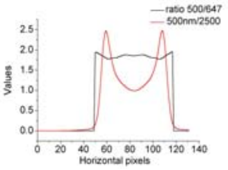
More in detail,observing the vertical profiles (taken on the axis of the flame)and the horizontal ones (taken at about the middle height of the flame),we can try some considerations:



Vertical profiles

The vertical profile shows a slight decrease of the ratio from bottom(high pixel number) to top probably due to two contribute:

- different index of refraction are possible for different soot aging
- local variation in laser fluence

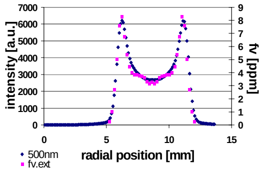


Horizontal profiles

The horizontal profile of the ratio is almost flat and the small variations are probably due to some residual chromaticity of the lens.

The almost perfect constancy of the ratio suggests that the maximum soot temperature is also constant through the flame even if in order to determine the peak temperature a calibration procedure is necessary. So, we can not determine the values of the soot distribution at this stage of the work.

Nevertheless a comparison of LII intensity profiles and soot distribution obtained whit an other independent technique should guarantee that the technique is correct.



This comparison is shown for a height of 30 mm from the burner mouth.

The LII intensity profile has been scaled to match the peak of soot volume fraction as determined with the extinction method in the same flame.

Conclusions

In this work a two-color LII incandescence technique has been developed for 2D imaging of soot volume fraction in a diffusion flame. The structure of the image of the ratio makes rather confident that the technique is correct and can be applied in a variety of experimental conditions.However, particular care must be take during the experiment, basically concerning:

- the flame instability
- the achromaticity of the detection system and the acquisition timing
- the laser beam quality.