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► **To cite this version:**

Amanda Pieyre, Takeshi Yokomori, Franck Richecoeur. Thermal Characterization of a Narrow Channel Wall by Thermographic Phosphor Thermometry. 8th European Combustion Meeting, Apr 2017, Dubrovnik, Croatia. hal-02369585

HAL Id: hal-02369585

<https://hal.science/hal-02369585>

Submitted on 24 Aug 2020

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Thermal characterization of a narrow channel wall by thermographic phosphor thermometry

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Abstract

The stabilization of a flame in a narrow quartz tube strongly depends on the thermal environment. To determine heat transfer and better understand the stabilization mechanisms of a flame in a narrow channel, wall temperature profile measurements are needed. The Laser Induced Phosphorescence (LIP) is used with the intensity ratio method to obtain temperature distribution of the outer surface of a 5mm inner diameter quartz tube within which a lean premix methane/air flame is stabilized. This study evaluates the ability of this method to capture a large temperature gradient on a small volume with a high curvature and compares the use of two phosphors.

Introduction

The recent need for micro-technologies has increased the development of small scale portable devices. In this context, the combustion in narrow channel has a great potential for small mechanical and heat power source devices and also electrical power supply. Indeed, the micro and mesoscale combustion takes advantages of the great energy density of hydrocarbon fuels which is sixty times higher than the one for classical lithium-ion batteries and has the advantage of unlimited and immediate recharge. Based on a 10% energy conversion efficiency, the energy density of a micro-combustor is six times higher than the one of a lithium battery [1]. Devices using narrow channel combustors could then be used for MEMS in various applications as biomedical, telecommunications or thrusters [1,3]. Nonetheless the size of these micro and mesoscale devices sets some limits to overcome for a broad industrial development. In fact, in those devices the large surface to volume ratio causes massive heat loss, which leads to flame oscillations, quenching and sets flammability limits [4].

For tube diameters below the quenching diameter, heat losses are so important that it leads to quenching and the only solutions to counter-balance the large heat losses of the flame consist in adding external energy to the system to assist and sustain the flame. The energy addition is usually over-sized and the total budget is negative (i.e. power used to maintain the flame is larger than power produced by the flame). The lack of knowledge of the interactions between the flame and the wall makes impossible a fine tuning of assistance to the flame. To quantify heat exchanges between the flame and the tube, the present study uses a tube diameter slightly above the quenching diameter so that heat transfers have a significant impact on the flame but the latter is self-maintained [1].

First, to determine heat transfer and better understand the stabilization mechanisms of a flame in a narrow channel, but also to obtain boundary conditions for numerical computations, wall temperature profile measurements are needed.

Several methods for temperature measurements are available, but since the outer wall and inner wall temperatures have to be measured, only a few are compatible. The Laser Induced Phosphorescence (LIP) was then selected for its semi-intrusive characteristic and good accuracy [5]. This method is based on the use of thermographic phosphors. Two thermographic phosphors were of interest in our case for their large temperature range and presenting no oxygen dependence, and mostly used in combustion cases: the dysprosium and praseodymium doped yttrium aluminium garnet (Y3Al5O12:Dy and Y3Al5O12:Pr) [5,6]. The use of these two phosphors is compared in accuracy, and according to their sensitivity to the temperature, to obtain a temperature map of the outer surface of a 7mm outer diameter quartz tube within which a premix methane/air flame is stabilized. The intensity ratio method is used to link the phosphor emission intensity to the temperature. We evaluate the ability of this method to measure the temperature on a small volume with a high curvature and subject to high temperature gradient.

The specific objectives of the paper are presented in Section 2. The experimental setup, the diagnostic, the phosphors and the validation method are described in Section 3. The temperature maps and centreline profile obtained and the evaluation of the method applied to small volumes is made in Section 4.

Specific Objectives

In this paper the specific goals are:

1- To evaluate the capacity of the Laser Induced Phosphorescence to measure temperature when applied to small and curved volumes subject to high temperature gradients.

2- To measure the temperature of the meso scale quartz tube outer surface with a lean premix flame stabilized inside at different equivalence ratio.

3- To compare the accuracy and sensitivity of two phosphors (YAG:Dy and YAG:Pr) .

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Experimental setup and introduction to LIP

The experimental setup shown in [Figure 1](#) is on purpose rather simplistic to better understand the heat exchanges between the wall and the flame and the flame stabilization mechanism. It is composed of a quartz tube of 5mm inner diameter and 1 mm thickness in horizontal position, inside which a lean methane/air premixture is injected and ignited. The speed and equivalence ratio of the flux are controlled by two massflow meters (REF). At functioning points of equivalence ratio and speed a flame can be stabilized inside the tube.

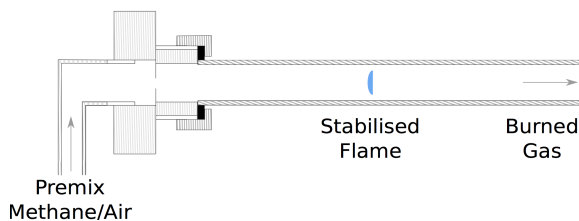


Figure 1: Experimental set up composed by a quartz tube within which a lean premixture methane/air flow is injected, and at functioning points a flame can be stabilised.

The method of Laser Induced Phosphorescence is used. A thin layer of a rare earth or transition metal doped ceramic material is painted on the tube and reaches the same temperature than the tube surface. When excited by a monochromatic UV light source, the ceramic emits a temperature dependent light. The emission spectrum is recorded and, after calibration, is processed to determine the surface temperature. This method has the advantages of being semi invasive, has a high spatial and temporal resolution, it can be used on broad temperature ranges depending on the phosphors used, it is insensitive to surface properties and robust against interferences [\[5\]](#). The thermographic phosphor thermometry requires three steps: the choice of phosphors, the measurement and calibration strategy and the film deposition method.

To measure the temperature distribution, the phosphors are fixed on the outer surface of the quartz tube using a phosphorescent binder. This binder is created by mixing phosphor powder (YAG:Dy Phosphor Technology, QMK66) and a high temperature inorganic binder (ZYP Coatings, HPC Binder). This paint is then sprayed on a strip of the outer surface of the quartz tube using an airbrush. The thickness of the paint layer must remain under 100 μm so that the thermal conductivity is not significantly modified, but also to avoid temperature gradient in the paint layer. The radiative transfers might also be slightly modified by the change of wall transmittance.

A methane/air premix flame is stabilized inside the tube, while the phosphor paint is excited by a Nd:YAG Laser quadrupled at 266 nm or tripled at

355nm depending on the excitation wavelength of the phosphor with a 10 Hz repetition rate (Quanta-Ray GCR-series). The emitted luminescence response of the phosphor paint is then recorded by an ICCD camera (Hamamatsu C12550 with image intensifier C9016-21). The emission light pathway is split in two. The two different pathways pass through two band pass filters, which wavelength corresponds to the two temperature dependent peaks of the emission spectra of the chosen phosphor. The two tube images for the two wavelengths are recorded on two areas of the same camera chip as shown in [Figure 2](#).

The intensity ratio method is then used to get back to the temperature: the ratio of intensities is made between the two tubes images and linked to temperature through a calibration curve. The calibration curve is made by replacing the tube in [Figure 2](#) by a tube furnace within which a sample of the same phosphorescent binder is placed. As for the tube, the ICCD camera records the subsequent emission of the phosphor and simultaneously the temperature is recorded by a thermocouple placed in contact with the sample. The range of temperature for the calibration goes from 300K to 1000K. (The calibration curve obtained corresponds to the literature.)

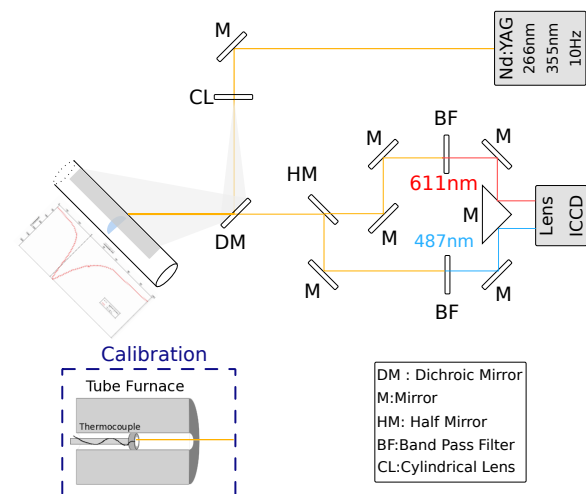


Figure 2: Experimental scheme of the Laser intensity ratio method using LIP and calibration method

Two thermographic phosphors were of interest in our case for their large temperature range and presenting no oxygen dependence, mostly used in combustion cases: dysprosium and praseodymium doped yttrium aluminium garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Dy}$ and $\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Pr}$). The YAG:Dy ($\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Dy}$) is excited at 355nm and has two temperature dependent peaks at 456nm and 497nm ([Figure 3a](#)). It is broadly used in the literature [\[5\]](#). The YAG:Pr ($\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Pr}$), less common, is excited at 266nm and has also two temperature dependent peaks at 487nm and 611nm ([Figure 3b](#)).

To record the emission spectra of YAG:Dy ([Figure 3a](#)) and YAG:Pr ([Figure 3b](#)), the camera in Fig.2 is replaced by a spectrometer in the calibration

configuration : the phosphor sample inside the tube furnace. The furnace is gradually increased in temperature and the emission spectra of the phosphor are recorded. The spectra are represented in Figure 3 normalised by the maximum of intensity. The dotted lines represent the temperature dependent peaks of each spectrum.

These emission spectra allow us to make a first analysis on the sensitivity of the phosphors with temperature. As the temperature increases, the intensity of the 487nm temperature dependent peak of YAG:Pr drops to a very low value. At high temperatures the YAG:Pr is then less accurate than at low temperatures.

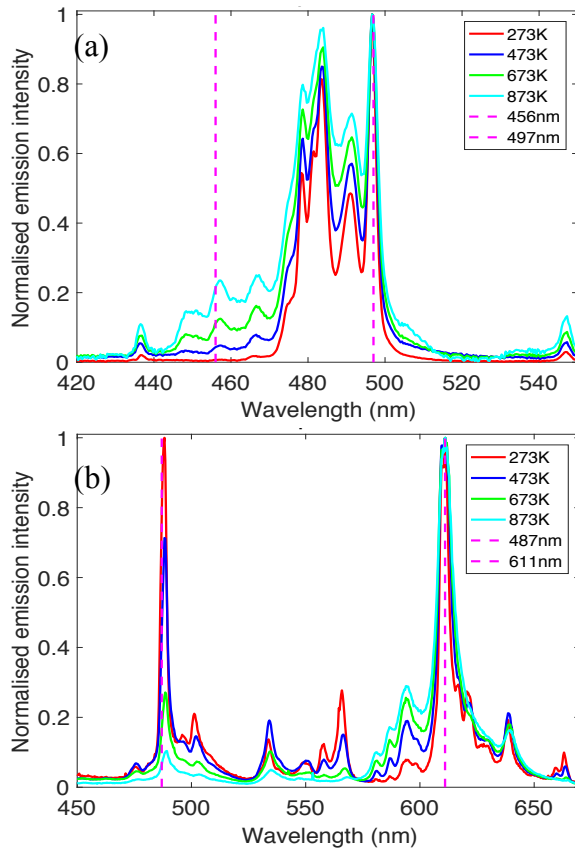


Figure 3: Normalised emission spectra of YAG:Dy (a) and YAG:Pr (b) showing the two temperature dependent peaks at various temperatures. The spectrum are normalised by the maximum value.

Results and Discussion

Thermocouple measurements on the outer surface

The LIP technique is subject to optical misalignments and distortions, and a comparison method is necessary to estimate the accuracy of this method applied to the measurement on the outer surface of a narrow channel. This method chosen was made using a 0.075 mm diameter type N thermocouple (Omega OPON-003), forced against the outer wall of the quartz tube and moved along the tube by a micro-displacement device (Thorlabs MTS50/M-Z8E). The temperature profiles obtained at equivalence ratio from 0.7 to 0.85 are drawn on Figure 4. The black dotted line highlights the flame front position. As expected, the maximum of temperature and the length of the cooling area both increase with the equivalence ratio.

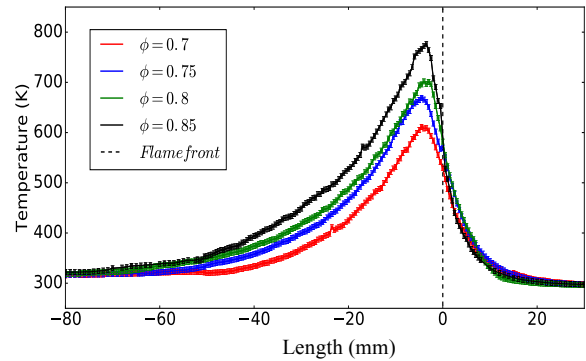


Figure 4: Temperature profiles measured by thermocouple forced against the quartz tube and moved horizontally by micro-displacement for several equivalence ratio. The black dotted line marks the flame front position. The flow direction is from right to left.

This thermocouple method gives a good accuracy since the theoretical errors for the temperature, the thermocouple and for the position the displacement are both given by constructors. Due to the very small diameter of the thermocouple, another imprecision can occur by the fact that the soldered joint is not directly in contact with the quartz tube's outer surface but with the surrounding air. The inaccuracies in temperature are estimated at +/- 10K and at 1mm in displacement. This method is cheap, easy to operate and accurate, but has its limits. As a result, it is used as a comparison method for the LIP technique on the outer surface of the quartz tube.

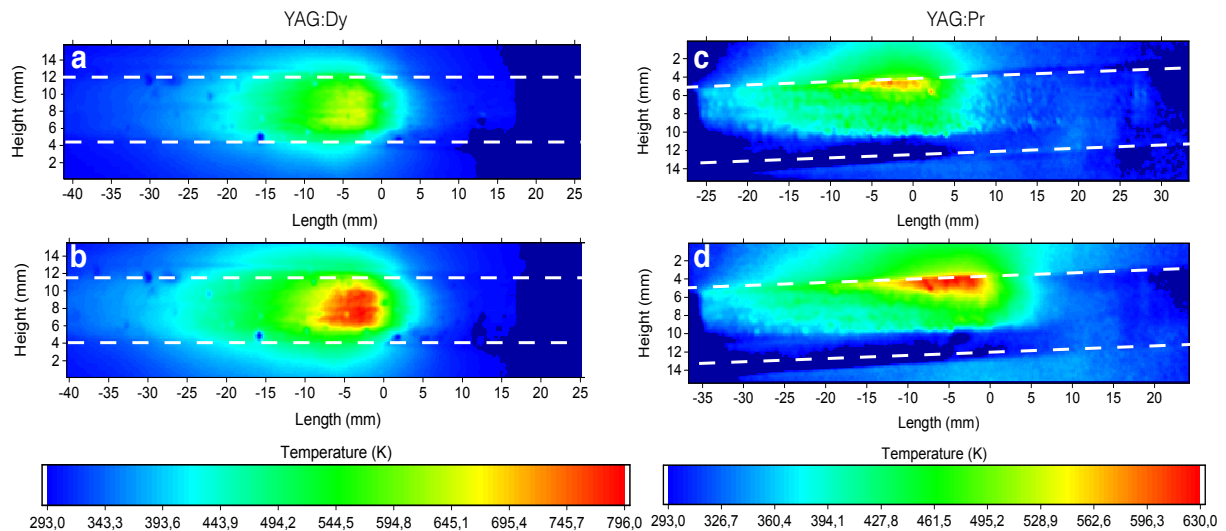


Figure 5: Temperature maps for YAG:Dy (a & b) and YAG:Pr (c & d) at equivalence ratio 0.7 (top) and 0.8 (bottom). The white dotted line highlights the tube. The flame position is at the length reference point 0. The flow direction goes from right to left.

Temperature maps

Once the intensity ratio method applied with the calibration curve, we obtain a temperature map **Figure 5** of the observed tube. Several experimental configurations are tested: two phosphors are compared at different equivalence ratio. In all this third section, the reference point is the flame front position, placed at the zero coordinates and the flow direction in all graphs goes from right to left.

The **Figure 5** shows a comparison of temperature maps for equivalence ratio 0.7 (top) and 0.8 (bottom) and for both YAG:Dy (left) and YAG:Pr (right). In both cases we can identify three areas on the temperature maps: the preheating zone located before the flame, the flame area where the temperatures are the highest, and the cooling area after the flame. The maximum of temperature reached with both equivalence ratio is higher for YAG:Dy than for YAG:Pr. Notable optical deformations can be observed on YAG:Pr (**Figure 5c & d**) temperature maps. Indeed, the flame area can only be observed on the upper part of the tube. This is due to laser misalignment with the tube: the tube must be perfectly orthogonal to the laser sheet.

To compare the thermocouple temperature profiles with the LIP method, the centreline profiles are extracted from the temperature maps. Indeed, to get the centreline profile, an average is made between the lines surrounding the maximum of temperature. As a result, the top graph in **Figure 6** shows the centreline profile extracted from the bottom temperature map for YAG:Dy, at equivalence ratio 0.8. Only a region of 75mm around the flame is recorded, the limit being set by the camera chip size. The temperature map and the plotted centreline profile show that the LIP technique correctly reproduces the high temperature gradient near the

flame on this small volume. The preheating and cooling zones are well represented, and the flame area can be clearly identified. However, optical imprecisions are also put in relief, when the flame area doesn't cover the entire tube's surface.

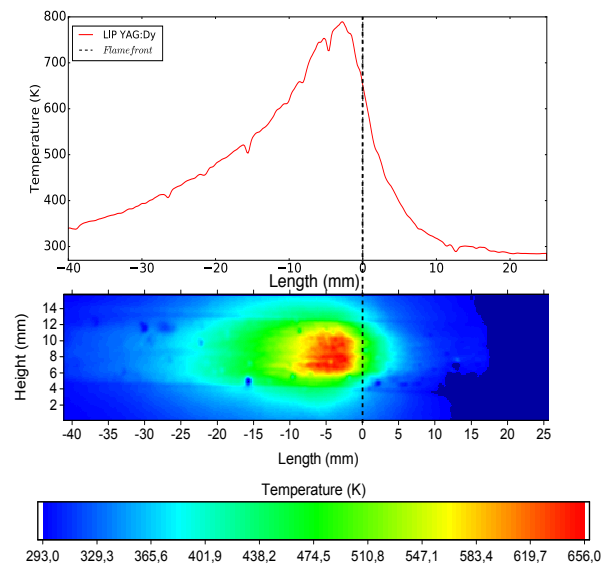


Figure 6: Centreline temperature profile (top) of YAG:Dy at equivalence ratio 0.8 extracted from the temperature map (bottom).

First to test the repeatability of the measurements, three acquisitions are made successively, in the same conditions at equivalence ratio 0.7, for the YAG:Dy phosphor. The **Figure 7** shows the three extracted centreline profiles. It gives indications on the order of magnitude of the imprecisions of the method, but also on the averaging in the centreline profile extraction. Nonetheless, the tendency of the temperature profile is similar between the three graphs.

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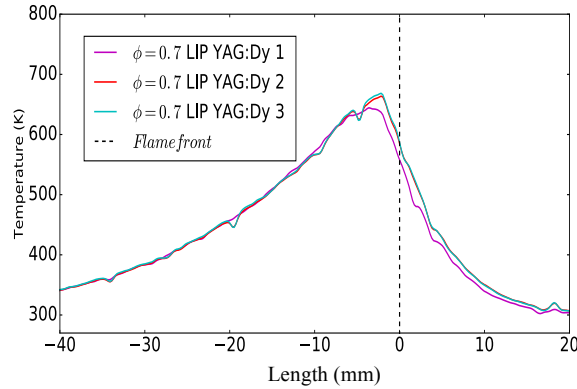


Figure 7: Evaluation of the reproducibility of the LIP measurements for YAG:Dy at equivalence ratio 0.7.

Centreline profiles comparison with the validation method

The centreline profiles are extracted from the temperature maps for each experimental configuration and compared with the validation method of thermocouple.

The first comparison in [Figure 8](#) is made between the centreline profiles of YAG:Pr (blue line), YAG:Dy (red line) and thermocouple profile (green dotted line) at equivalence ratio 0.7. This comparison shows that the YAG:Dy predicts with more accuracy the preheating zone before the flame front, but the maximum of temperature and cooling zone is 50K overestimated. The YAG:Pr centreline is less smooth, and the preheating zone and maximum of temperature is not well reproduced. Nonetheless the cooling zone matches with the thermocouple profile.

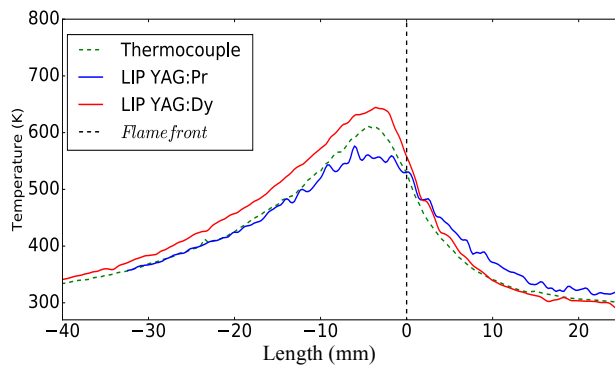


Figure 8: Comparison of centreline temperature profile of YAG:Pr and YAG:Dy to the thermocouple profile for the equivalence ratio 0.7.

The second comparison between the same graphs but for equivalence ratio 0.8 in [Figure 9](#) shows confirms the tendencies observed in the previous figure except for the YAG:Pr cooling zone. It can be explained by the fact that since the maximum temperature is more important, the cooling zone is

also higher in temperature, and as a result not well predicted by YAG:Pr.

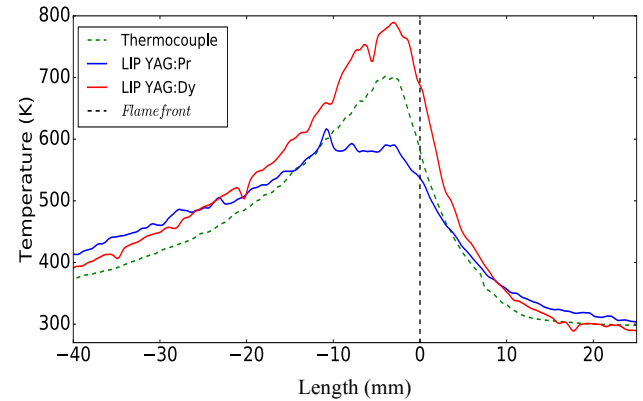


Figure 9: Comparison of centreline temperature profile of YAG:Pr and YAG:Dy to the thermocouple profile for the equivalence ratio 0.8 .

Error bars

With the reproducibility test made in [Figure 7](#) for the temperature inaccuracy, but also by taking in account the optical distortions for the spatial errors, qualitative error bars are represented on the [Figure 10](#). This graphs show that the tendencies are well reproduced by the LIP measurements, but this method needs improvement on accuracy.

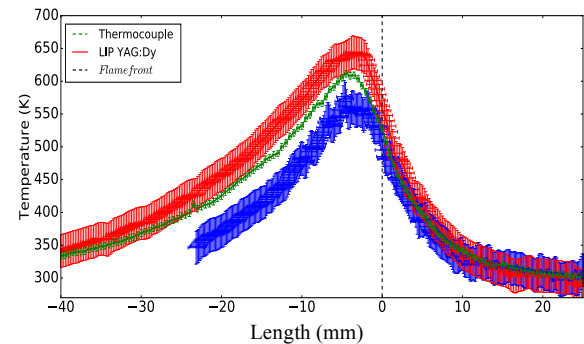


Figure 10: Qualitative errors bars on the Laser Induced Phosphorescence method using intensity ratio.

Conclusion

The present study aims at measuring the wall temperature distribution along a 7mm outer diameter quartz tube with a stabilized flame inside, in order to evaluate the heat flux around the flame. The study shows that the LIP method can be used on small volumes with a great curvature and high temperature gradient. Expected optical deformations were observed on temperature maps, however the temperature gradient was correctly reproduced. Two phosphors were compared and their different sensitivity with temperature impacts the quality of the measurements according to the distance to the flame

and the equivalence ratio. For more accuracy and in further work, the co-doping with these two phosphors is considered.

The intensity ratio method was used in a first step to make sure that measurements could be done on a small volume with a high curvature. For further work and to obtain a better accuracy, the LIP lifetime method has been proven to be more sensitive to temperature and more accurate than intensity ratio but harder and more expensive to set up.

Acknowledgements

This study was pursued in the frame of the research project ANR-14-CE05-0030-01 coordinated by EM2C laboratory.

The stay of A.Pieyre in Keio University has been supported by the Erasmus Mundus EASED program (Grant 2012-5538/004-001) coordinated by CentraleSupélec.

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