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► **To cite this version:**

Amanda Pieyre, Takeshi Yokomori, Franck Richecoeur. Determination of wall temperature in a narrow channel by thermographic phosphor thermometry. 54th Symposium (Japanese) on Combustion, Nov 2016, Sendai, Japan. hal-02369573

HAL Id: hal-02369573

<https://hal.science/hal-02369573>

Submitted on 24 Aug 2020

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Determination of wall temperature in a narrow channel by thermographic phosphor thermometry

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Abstract: The stabilization of a premixed methane/air flame in a narrow quartz tube strongly depends on the thermal environment, especially on convective and conductive heat exchanges between walls and gas. 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, temperature profile measurements are needed. Several methods for temperature measurements are available but since the outer wall, inner wall and gas flow temperature 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. This method is based on the use of thermographic phosphors. Thus the thermographic phosphor YAG:Pr was selected for its large temperature range. It is composed of trivalent praseodymium (Pr³⁺) ions doped into an yttrium aluminum garnet (YAG) host. In a first step it is bound to the outer wall surface of a 7mm outer diameter cylindrical quartz tube. A premixed methane/air flame is stabilized inside the tube and emission intensity is captured by an ICCD camera. The intensity ratio approach is then used to determine the temperature map of the wall.

Keywords: Mesoscale combustion, Laser induced phosphorescence, Temperature measurements, Laminar flame

1. Introduction

In mesoscale combustion, the analysis of thermal exchanges between the walls and the flame is a necessary step toward the understanding of a flame's stabilization mechanism in a narrow channel. The goal of this study is then to obtain a map of temperature of the external wall of a 7mm outer diameter and 1mm thick quartz tube using Laser Induced Phosphorescence (LIP) and intensity ratio method. The LIP method has the advantage of being semi-intrusive and giving a good accuracy [1]. The intensity ratio method exploits the fact that the time-integrated luminescence intensity of thermographic phosphors depends on temperature.

2. Temperature measurements with the LIP method

The thermographic phosphor YAG:Pr is used for its large range of temperature. It also has two temperature dependent peaks in its emission spectra, which increases the accuracy of the intensity method compared to a phosphor with only one temperature dependent spectral band. Indeed, since the two spectral band luminescence intensity are equally influenced by critical factors, like excitation energy or phosphor layer's homogeneity, the normalization of one spectral band to another limits the influence of these factors [1].

To measure the temperature, this phosphor needs to be fixed on the outer surface of the quartz tube. Therefore, a phosphorescent binder is created by mixing phosphor powder and a high temperature inorganic binder (Aremco Ceramabind 644). This paint is then sprayed on a strip of the outer surface of the quartz tube as shown in Fig.1. 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. It is to be noted that the radiative transfers might also be slightly modified by the change of wall transmittance.

A methane/air premix flame, equivalence ratio of 0.8, is stabilized inside the tube, while the phosphor paint is excited by a Nd:YAG Laser (Quanta-Ray GCR-130) quadrupled at 266 nm with a 10 Hz repetition rate. The emitted luminescence response of the phosphor paint is then recorded by a 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 of 487nm and 611nm corresponds to the two temperature dependent peaks of the emission spectra of the chosen phosphor. The two tube images for the two wavelength are recorded on two areas of the same camera chip as shown in Fig.1 and Fig.3.

Then the ratio of luminescence intensity is made between the two images for the two wavelength. This intensity ratio is linked to the temperature through a calibration curve, made by painting a 1mm diameter thermocouple with the same phosphorescent paint used on the tube. This thermocouple is placed in a temperature controlled air flow [2] and at the same position as the tube shown in Fig.1. As for the quartz tube, the painted thermocouple is excited by the laser and the emission intensity is recorded by the camera. Simultaneously, the temperature displayed by the thermocouple is recorded. The range of temperature for this in-situ calibration goes from 300K to 700K. The calibration curve, shown in Fig.2, corresponds to the literature [3]. The margins of errors are shown on the Fig.2 taking in

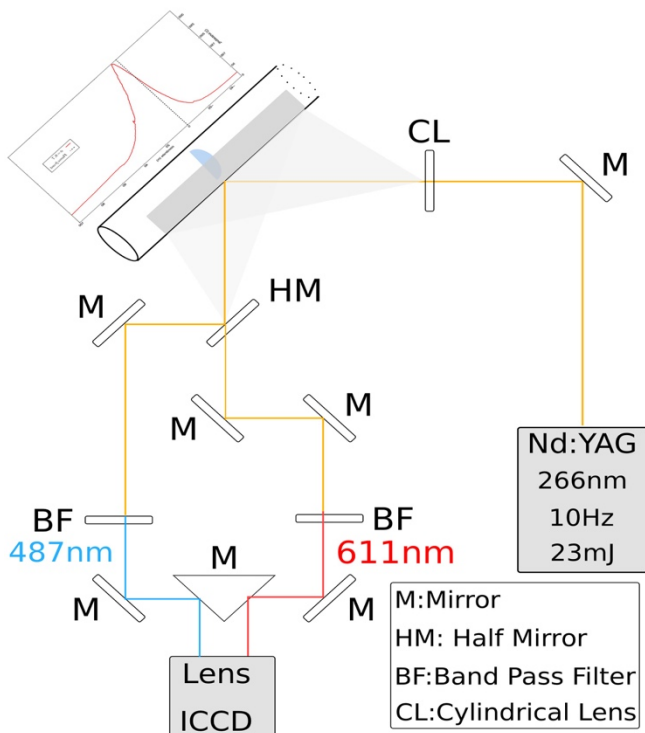


Figure 1 : Experimental set up scheme showing the light pathway from the laser to the camera. The red graph displayed above the tube is a temperature profile obtained with a thermocouple (Fig.4).

account numerical errors and the accuracy of the thermocouple.

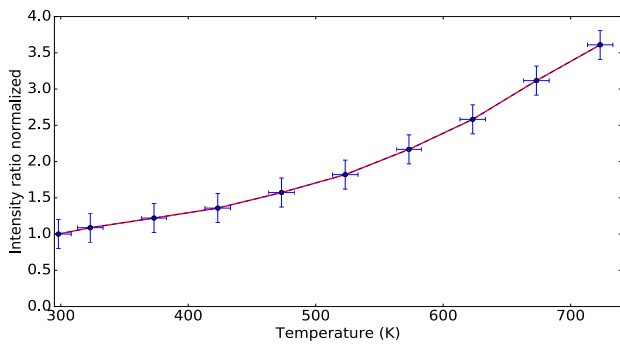


Figure 2 : The calibration curve for the intensity ratio method shows the dependence of the intensity ratio on the temperature. The intensity ratio of the flame is normalized by the room temperature intensity ratio.

3. Results

The Fig.3 shows the camera chip image of intensity distribution with and without the flame in the tube. As the temperature increases, the emission intensity at 611 nm increases. On the contrary, the emission intensity at 487 nm decreases with the increase of temperature. This phenomenon is in accordance with the literature [3].

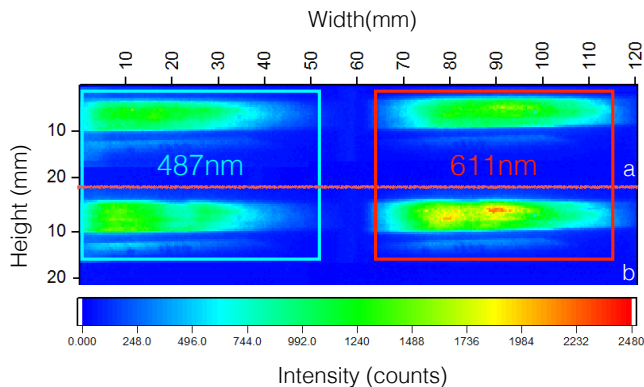


Figure 3 : Camera chip image of intensity distribution a. at room temperature and b. with the flame, and for the two wavelength 487nm (left) and 611 nm (right). The gas flow goes from the right to the left.

A comparison is made on Fig.4 between the temperature profile of the outer wall measured by a thermocouple (blue curve) and an extracted temperature profile from the centerline of the temperature map obtained (red curve) (upper graph) and the temperature map obtained with the LIP method (lower graph). The measurement with the thermocouple 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).

In these graphs, the black line shows the flame front position. This comparison shows good results of temperature distribution and for the preheating of the fresh gas upstream from the flame. Nevertheless, it also shows some limits and inaccuracy of the LIP process: highest temperatures are only located at the center line of the map (lower graph) and the maximum measured by LIP is 50K lower than the one measured by thermocouple Fig.4 (upper graph). Fixing these inaccuracies will be the object of further research.

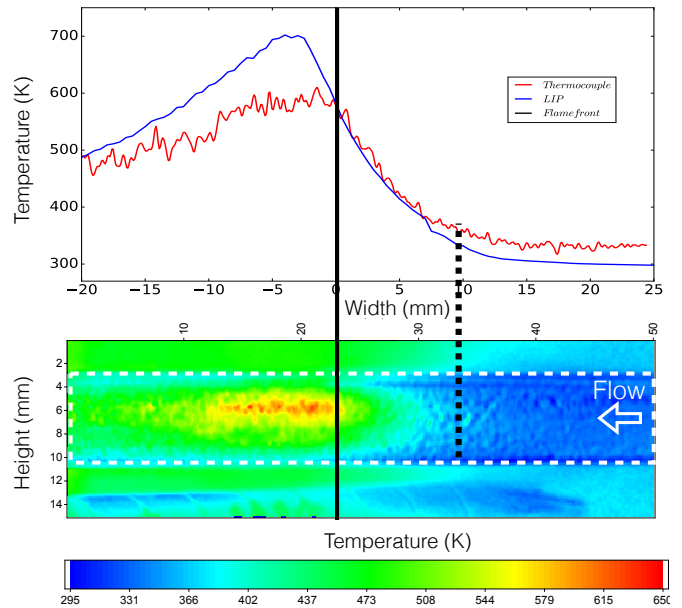


Figure 4 : Temperature map on a 7mm outer diameter quartz tube outlined by the white dotted rectangle, with a stabilized premix methane/air flame inside the tube, and with an equivalence ratio of 0.8. The flame position is indicated by the black line. The black dotted line represents the start of the preheating zone of the fresh gas by the flame. The gas flow goes from the right to the left.

4. Conclusion

The LIP and intensity ratio method are used to draw a temperature map of a 7mm diameter quartz tube, with a premix methane/air flame stabilized inside. This method shows great potential for temperature measurements in mesoscale and microscale combustion.

The next step of this research would be to better approximate the temperature distribution, and to get the temperature map from the inner wall of the quartz tube.

4. Acknowledgements

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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