Two-line OH PLIF temperature measurements of flames near a quenching plate

David Escofet Martin, Y.C. Chien, D. Dunn-Rankin
Mechanical and Aerospace Engineering, University of California Irvine
Irvine, California, US

1 Introduction

OH and temperature are key quantities to understand diffusion flames. Several laser non-intrusive techniques are available for making measurements of these properties: Rayleigh or Raman scattering, fluorescence based techniques, and CARS. Laser induced fluorescence can be used for flame thermometry as long as a fluorescent molecule can be excited through two different transitions.

Fluorescence stands out as a valuable method because of the high signal-to-noise ratios achieved through gating of the signals both in the time domain and frequency domain.

Some suitable fluorescing species are present naturally in flame conditions, such as NO and OH, although using them can limit applicability due to low concentration in some important areas of the flame. Unfortunately, seeding the flow with tracers, such as NO and Indium, can be sometimes a difficult task, and it has an impact in the flame chemistry. Hence, in this experiment we will focus on two-line OH thermometry due to the excellent signals and 2D imaging capabilities with high spatial resolution. In addition, as mentioned before, seeding is not necessary since OH is naturally present in the flame, particularly in the important high temperature regions. In this paper we report 2D temperature measurements of an atmospheric pressure non-premixed coflow burner under the special conditions where the flame is impinging on a relatively cool wall that produces a quenching interaction.

2 Fundamentals of Two-Line Temperature Imaging

The basis for two-line OH temperature PLIF has been described in the past [1], [2], and only a brief description is given here. The linear LIF signal S is a function of:

$$S = \eta I N_t (2J'' + 1) \exp(\frac{-E}{kT}) B G \Phi(T, J')$$

Where η is the optical detection efficiency, I intensity of the laser power, J’’ the rotational quantum number of the excited ground state and J’ the rotational quantum number of the excited upper electronic state, N_t is the total number of OH molecules, E is the energy of the ground state, B is the absorption Einstein coefficient, G is the spectral overlap integral between laser and molecular absorption profile, and Φ is the fluorescence quantum yield. Assuming similar collection efficiencies due to using the same camera, camera filter and the same laser setup for two different transitions (1 and 2), we can obtain:

Correspondence to: descofet@uci.edu

$$\frac{S_1}{S_2}=\frac{I_1}{I_2}\frac{(2J_1''+1)}{(2J_2''+1)}\exp\left(\frac{-(E_1-E_2)}{kT}\right)\frac{B_1}{B_2}\frac{G_1}{G_2}\frac{\Phi_1(T,J')}{\Phi_2(T,J')}$$

Where the ratio S_1/S_2 at every pixel of the camera is a function of several constants, temperature, laser intensity, both overlap integrals, and the ratio of both quantum fluorescent yields. The spectral overlap between laser profile and absorption line profile is assumed to be the same for both transitions, which is a source of a small systematic error, even though the laser profile is very similar for both transitions. Since we are working with the same laser setup in a narrow range of wavelength, Doppler and collisional effects depend on the rotational quantum number, but in the calculations we assume that line broadening for the two transitions is similar; this is the easiest assumption to relax to improve the measurements using a theoretical model to adjust the change in spectral absorption profile.

The quantum fluorescence yield ratio is difficult to determine because of the complex behavior of the collisions and energy exchange through vibrational and rotational energy transfer (VET and RET) in the nonequilibrium upper electronic state. From a theoretical standpoint the best way to solve that problem, as has been proposed [3], is using two transitions that share a common upper state. In that way the ratio of fluorescence yield would be unity. Unfortunately, this ideal situation is not possible because the exponential dependence of the energy difference in the ground state (for the OH molecule) makes this energy difference too small so that the sensitivity of the measurement becomes very low, reducing dramatically the signal to noise ratio of the measurement. The most common technique for finding the ratio is to do so experimentally by using an alternative temperature measurement [4] for a certain position of the flame, and then using that measurement to calculate this ratio. This last method has not been used in this case because of the spatial resolution of the alternative method (e.g., thermocouple) would be far worse than the one offered from the OH two-line PLIF, making it rough due to averaging and the high gradients present in the flame. For that reason we assumed rapid rotational thermal stabilization in the upper electronic state [5] that would lead to a ratio that is approximately 1. This assumption produces a systematic error in the measurements but again the error can be bounded as relatively small based on expected deviations from the unity fluorescence yield ratio.

The final decision of the transition pair has taken into account several factors: transition strength, transition isolation from neighboring transitions, and maximum energy difference in the ground state with no interference from surrounding species.

3. Experiment

3.1 Burner

The experiments are conducted with a coflow burner and a 2 mm thick stainless steel plate progressively lowered toward the burner surface so that it gradually quenches the flame [6], [7]. The stainless steel coflow burner is 13 cm tall and has a 4 cm outer diameter. At the exit, the burner has a 2.13 mm inner diameter center tube carrying fuel, and air is provided separately through a concentric outer ring. The air is designed to have a uniform laminar flow distribution at the exit after it passes through a bed of beads and a honeycomb mesh close to the exit. Inside the burner, the length of the tube is sufficient to ensure fully developed laminar flow at the exit for the range of desired Reynolds numbers. The metal plate used as the quenching surface is 50 mm square. It is indirectly connected onto a vertical-axial translation stage through two cylindrical ceramic threaded posts. The diffusion flame used for this work had flow rates equivalent to a constant nominal speed of 20 cm/s for both methane and air at the burner exit.

3.2 Laser and detection system

The set up used for this specific realization of the technique includes a 10 Hz Surelite III Nd:Yag laser, followed by a Vista dye laser using (Rhodamine 590 dye dissolved in methanol) and a wavelength extender. The sheet forming optics comprise a spherical lens plus a cylindrical lens, forming a sheet with a height of 3 cm. The pulse energy was kept below 4mJ where it could be observed experimentally that all the transitions used for the 2 line OH PLIF were linear [8], [9]. The linearity of the signal was checked by comparing the overall integrated signal of the fluorescence images from the camera with the average energy power from the laser used for the images. The transitions selected from the A-X (1,0) band are the P1(3) and P1(10) around 283 nm.

The fluorescing light was collected using an EM-ICCD PIMAX-4. The filter used (Semrock FF01-320/40-25) offers very good transmissivity (70%) to collect the light from the A-X(0,0) transition. The images were taken using a 300 ns gate, which is long enough to collect the fully integrated signal of the fluorescence and short enough to suppress the background chemiluminescence. Absorption through the flame is considered negligible; this is because the inner diameter of the burner is only 2 mm, and there is not enough OH concentration to make absorption relevant. 200 images were collected for every transition and position. After taking the fluorescence images for each transition, the flame was moved away, putting instead a quartz dye cell with a diluted mixture of methanol with dye, in order to accurately correct for intensity variations across the laser sheet, repeating that procedure for all the positions and transitions.

3.3 Image processing

200 images are averaged before ratioing to obtain a better signal to noise image. The averaged image is weighted with the laser intensity mapping obtained from the fluorescent dye diluted mixture. The images are aligned one by one since the laser intensity mapping is taken for every transition due to nonlinear behaviors in the doubling processes. The images are corrected using the average of the images (instead of 2 images) by using the overall integrated signal for each sequence of pictures. Finally, isolating temperature from the previous equation, a temperature ratio is obtained for each pixel. In order to only obtain meaningful temperatures, a product of both averaged intensity transitions is computed, and a constant is used to limit the low end in the not meaningful temperature data, assigning 0 K where it is not meaningful.

4 Results

All the measurements are repeated for different relative positions of the flame with respect to the plate. The lower temperature limit is 1000K because OH only exists at temperatures above 1000K. Summarizing, the potential sources of systematic errors include: assumption of the same line broadening for both transitions P1(3) and P1(10), assumption of similar quantum fluorescent yield, and nonlinear averaging due to slightly movements in the flame position. While it is difficult to quantify these systematic errors precisely, evidence from the literature, the range of temperatures detected, and the sensitivity of temperature to these assumptions, suggests that they are relatively small (certainly below 10% in total).

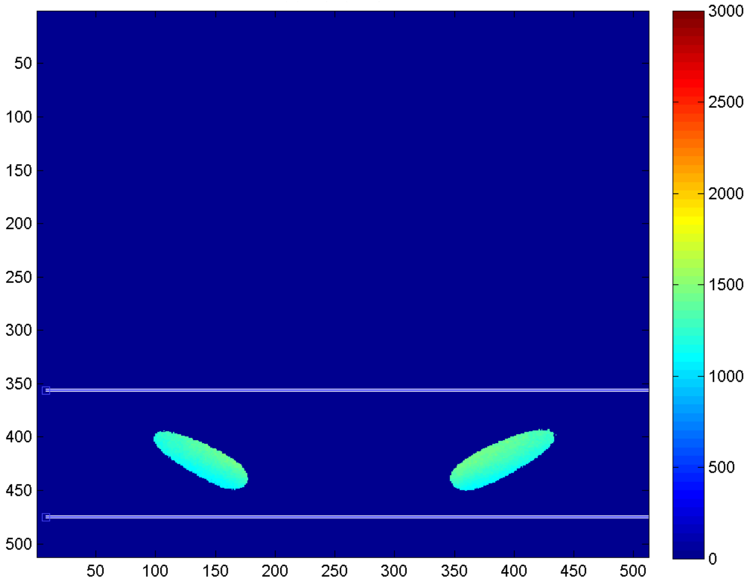

Figure1 Temperature measurement with a distance plate burner of 3mm; x and y axes show number of pixels

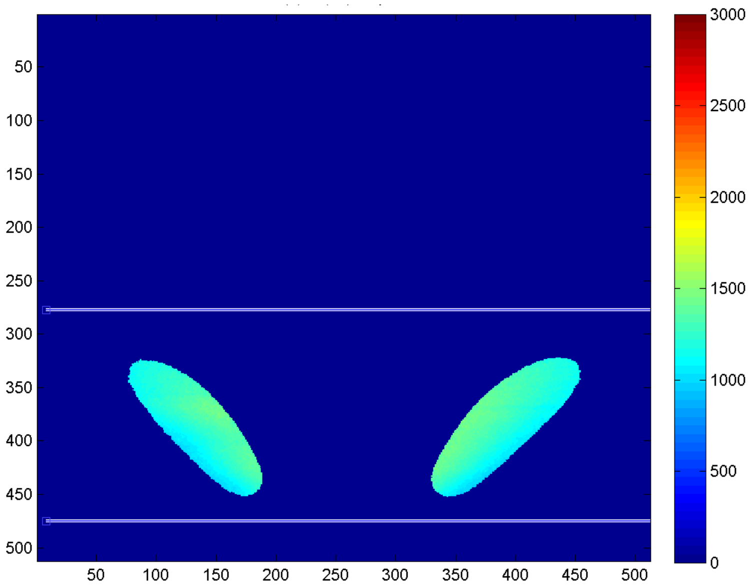

Figure 2 Temperature measurement with a distance plate burner of 5mm; x and y axes show number of pixels

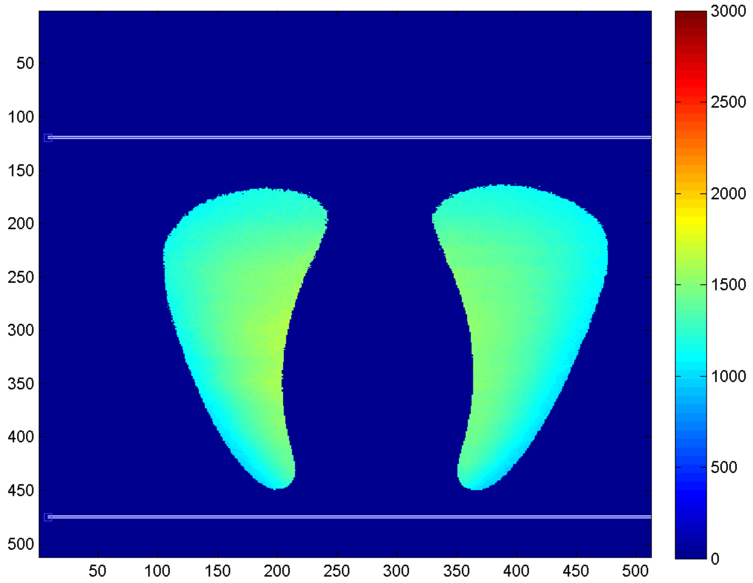

Figure 3 Temperature measurement with a distance plate burner of 9mm; x and y axes show number of pixels

5 Conclusions

Two-line OH PLIF thermometry measurements for a steady diffusion coflow flame are shown. The results are reasonable and in good agreement with the previous diagnostics applied in the same burner [10], e.g., the hottest part of the flame coincides with the positive gradient of the OH concentration and the Abel transformed OH chemiluminescence images. As predicted, the lowest temperature measured is 1000 K, as there is insufficient concentration of OH below these temperatures.

The images also support the heat transfer studies shown in [11]. For example, the peak flame temperature remains approximately constant through all the heights of the plate relative to the burner. This finding supports previous experimental results of similar overall heat transfer to the plate for all the plate-to-burner heights but with a significantly different spatial distribution of the heat flux to the plate.

6 References

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