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2D-RAYLEIGH SCATTERING THERMOMETRY IN POST-FLAME: POLARIZATION STRATEGY

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Abstract. *2D-Laser-induced Rayleigh scattering thermometry (2D-LRST) was applied in temperature investigation of premixed natural gas (NG) flames. The experimental strategy used was the polarization technique employing a laser sheet. The scattering images with laser (266 nm) in the S-polarization and in the P–polarization directions (respectively, electric field perpendicular and parallel to the detection direction) were registered. Obtaining the difference between both signals, the spurious background radiation due to non-polarized scattering was discarded and the post-flames temperatures were determined. Experimentally, the temperature of a narrow region of each flame was firstly obtained with focused laser radiation. The experiments were repeated with the laser sheet and the temperature distribution were corrected multiplying the data by a calculated correction factor f. Experimental post-flames temperatures obtained in this paper presented values up to 301K lower than the adiabatic temperature calculated by the Gaseq program. This is due to significant heat losses to the environment for the low fuel mass flow used. The 2D-LRST using a laser sheet presents interferences that are difficult to avoid experimentally but good results are achieved if a correction of the temperature distributions in the flames is made based on the results obtained through scattering Rayleigh thermometry with focused laser radiation.*

Keywords: laser-induced Rayleigh scattering thermometry, 2D-temperature distribution, natural gas

1. INTRODUCTION

Rayleigh scattering corresponds to the elastic scattering of light from atoms, molecules and particles that are much smaller than the wavelength of the incident light. The scattering amplitude is proportional to the number of scatters. When a polarized light is employed, the scattered radiation presents maximum amplitude in a plane perpendicular to the electric field (**S**-polarization) and minimum in a plane parallel to this direction (**P**-polarization) (Miles *et al*., 2001).

The Rayleigh thermometry technique is non-intrusive, experimentally simpler and cheaper than other optical methods, such as LIF (Laser-Induced Fluorescence) or CARS (Coherent Anti-Stokes Raman Spectroscopy) (Miles *et al*., 2001; Sutton *et al*., 2004; Sutton *et al*., 2006). The measurement range for Rayleigh scattering thermometry is 293 K - 2773 K (Childs and Greenwood, 2000).

Laser-induced Rayleigh scattering thermometry (LRST) has potential to provide 2D information in combustion environment. However, for practical applications, there are challenges to be overcome once the technique presents an additional difficulty related to the important interference of spurious scattered light due to reflections from the burner itself and from other optical components, as lenses and windows through the beam path, often referred to as stray light (Kristensson *et al*., 2015). Spurious radiations frequently present higher intensity than Rayleigh's itself, especially at elevated temperatures, making it unfeasible to be directly applied on combustion systems.

On single-point temperature measurements, good results are achieved through the stray light diminishment by the application of masks and taking strict care regarding the optical system alignment. **S**-polarized laser light is utilized with the scattering detection set at 90º (maximum Rayleigh scattering). The background effects are verified through experiment rounds conducted for measuring argon and helium scatterings, from which, the results are compared to standard values, corresponding to a 75 ratio (Sutton *et al*., 2006).

In 1986, Fourguete *et al.* (1986) proposed a 2D time-resolved LRS for mapping the temperature field of a turbulent non-premixed methane-hydrogen flame, using a multpass cell to form a sheet of light. The background contributions were determined by imaging the scattered light from helium issued from the axial co-flow of the burner. They verified that the stray light could be reduced to ~10 percent of the maximum Rayleigh signal.

More recently, some experimental strategies have been presented that improve the accuracy and reliability of 2D LRST, such as the Filtered Rayleigh Scattering (FRS) (Elliot *et al.*, 2001) and the use of Rayleigh thermometry with structured illumination (Structured Laser Illumination Planar Imaging– SLIPI) (Kristensson *et al.*, 2015).

The principle applied by FSR is that Rayleigh scattering is enlarged when compared to the incident's light wavelength by the Doppler effect, nevertheless, such phenomena does not happen to spurious scatterings. Due to that, FSR has to be performed with a narrowband laser that matches exactly an absorption line of a molecule or atom used as a filter. The temperature evaluation routine must take into account species-specific Rayleigh cross sections and spectral shape of the emissions.

In the SLIPI, the laser sheet intensity is modulated through adequate optical components (as a Ronchi grating or two-faceted optical component). The Rayleigh scattering signal follows the same modulation, what does not happen with the stray light signal. An image post-processing is required in order to minimize the background influence.

In the present study, the Rayleigh thermometry technique using the polarization strategy was applied to natural gas premixed flames on rich, stoichiometric and poor conditions. The adopted strategy consisted of the application of polarized laser radiation with polarizations perpendicular (**S**) and parallel (**P**), in respect to the detection direction and executing a signal subtraction, **S-P**, in order to mitigate the spurious radiation presence. Great results were obtained when making use of focused laser radiation (1D, one-dimensional, thermometry); nonetheless, a correction factor was noticed to be necessary when utilizing a laser sheet (2D, two-dimensional, thermometry) as a mean to achieve adequate results. The correction factor was obtained by performing the 1D thermometry on the same flame. The data treatment was executed through a routine implemented in LabView.

2. THEORECTICAL DESCRIPTION

LRS technique details can be found in Laurendeau (1988) and Fourguete *et al.* (1986). Rayleigh scattering electromagnetic radiation occurs when the scattering particle dimension is roughly 10 times smaller than the incident light wavelength. The intensity of Rayleigh scattered light is directly proportional to the laser power, the gas density, and is dependent on the cross section of the gas that is being investigated. For an ideal gas mixture, the contributions to the total signal depend only on each component's molar fraction (x_i) and an effective scattering cross section (σ_{eff}) is obtained thought the individual scattering cross sections (σ_i):

$$\sigma_{eff} = \sum_i x_i \sigma_i \tag{1}$$

The intensity of scattered light can be written as:

$$I_{RS} = \beta \Omega_c V_c N_T I_L \frac{\delta \sigma_{eff}}{\delta \Omega} \tag{2}$$

where I_{RS} is the Rayleigh scattered signal power, β is the detection efficiency, Ω is the solid angle of the collection optics (sr), V_c is the collection volume (cm^3), N_T is the total number density of the medium and $\frac{\delta \sigma_{eff}}{\delta \Omega}$ is the differential effective cross-section given by:

$$\frac{\delta \sigma_{eff}}{\delta \Omega} = \frac{3}{8} \pi \sigma_{eff} (cos^2 \varphi cos^2 \theta + sen^2 \varphi) \tag{3}$$

where φ corresponds to the polarization angle and θ to the scattering angle. If both polarization and scattering angles are 90º (usual experimental configuration) we obtain from (2) and (3):

$$I_{RS} = \frac{3}{8} \pi \beta \Omega_c V_c N_T I_L \sigma_{eff} \tag{4}$$

For an ideal gas mixture, $N_T = P/kT$ (k is the Boltzmann constant, P, the pressure and T, the temperature) gives the total number density of the medium and the Rayleigh scattering method can be used for thermometry if the pressure P and the effective cross-section are constant. The temperature can be easily determined using relative I_{RS} signals in order to eliminate the dependence in $\beta \Omega_c V_c$. Usually LRST involves two scattering measurements, one of them in a reference sample (for example, air at room temperature - T_{air}), and the other, in the combustion environment. This way, from Eq. (4):

$$\frac{I_{RS,air}}{I_{RS,comb}} = \frac{N_{air}\sigma_{eff_{air}}}{N_{comb}\sigma_{eff_{comb}}} \qquad (5)$$

where $I_{RS,comb}$ and $I_{RS,air}$ are, respectively, the intensity of Rayleigh scattering in combustion and in air environments, normalized with respect to the intensity of the incident laser. Considering ideal gas behavior and constant pressure condition ($P = P_{air} = P_{comb}$), Eq. (5) can be written as:

$$\frac{I_{RS,air}}{I_{RS,comb}} = \frac{\frac{P}{kT_{air}}\sigma_{eff_{air}}}{\frac{P}{kT_{comb}}\sigma_{eff_{comb}}} \qquad (6)$$

Rearranging Eq. (6):

$$T_{comb} = T_{air}\frac{I_{RS,air}\sigma_{eff,comb}}{I_{RS,comb}\sigma_{eff,air}} \qquad (7)$$

In 2D-temperature studies, it is necessary to determine the relative species concentrations in all the regions and to know the Rayleigh scattering cross sections of each species. The determination of temperature may be limited to some specific spatial regions, for example the post-flame region of a premixed flame as in the present paper, where only the combustion products are present. If the effective cross section of the reactants and products remains constant during the combustion process and through all regions of the flame, the 2D-temperature can be determinate with precision. Many binary mixtures of hydrocarbons and hydrogen satisfy this condition (Fourguete *et al*., 1986).

3. EXPERIMENTAL

The experimental arrangement includes a commercial LaVision Rayleigh thermometry equipment (Fig 1). The setup consists of a fourth harmonic (266 nm) Nd:YAG laser (Quantel, Brilhant B) working at an energy level of 90 mJ, with a 9 ns pulse duration and a 10 Hz frequency. A laser sheet of ~60 mm × 580 µm was produced employing a plano-convex spherical lens and a plano-concave cylindrical lens (*F*= -100). The laser sheet was positioned 10 mm above the burner in order to avoid reflections originated from its edges. An ICCD camera (LaVision, High Intensified Relay Optics) with an array size of 1376×1040 pixels was positioned at 90º to the scattered light. The UV camera objective (Nikon, 50 mm, f# 2.8), with a [266±5] nm filter, coupled to the ICCD produced images with a resolution of 0.0583581 mm/pixel. The Rayleigh strategy used was to register the scattering image with laser in the **S**-polarization and **P**–polarization directions (respectively, electric field perpendicular and parallel to the ICCD direction). The polarization of the laser was automatically changed during the images acquisition with the use of a polarization rotator. Each result is an average of 200 sets of images.
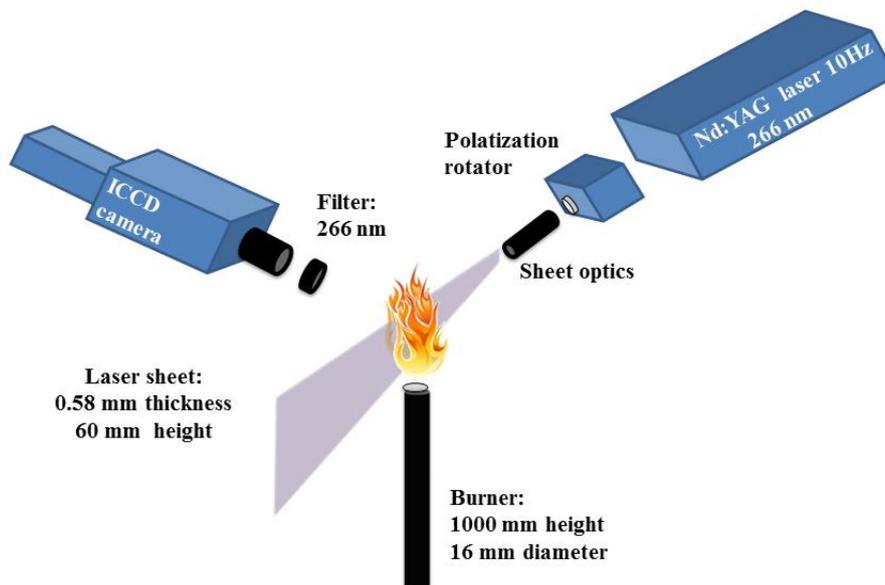

Figure 1. Experimental setup for laser Rayleigh scattering thermometry (LRST).

Temperatures of three premixed flames of natural gas (NG, 0,195 g/s) and air where studied (ϕ = 1.65, 1.05 and 0.81). The parameter ϕ is the equivalent ratio, defined as:

$$\phi = \frac{m_{fuel}}{m_{air} R_{est}} \qquad (8)$$

where R_{est} is the $\frac{m_{fuel}}{m_{air}}$ ratio for the stoichiometric reaction .

During the experiments, a good background correction was not possible when employing the laser sheet. In order to obtain reliable 2D-temperature distribution, the temperature of a narrow region of each flame was obtained without the plano-concave cylindrical lens (focused laser) and the temperature distribution were corrected multiplying all the data by the obtained correction factor f in this region, as described in the next section. The temperature obtained with focused laser is denominated in this paper as T_{1D} (linear) and the one obtained with the laser sheet, T_{2D} (planar).

In order to verify the laser intensity influence on the temperature results, some experiments were carried out by varying the incidence laser intensity between 4 mJ and 100 mJ, with the focused laser beam.

The species concentrations of the products and adiabatic flame temperatures of combustion were determined using the Gaseq 0.79 software (Moley, 2005) considering adiabatic conditions at constant pressure and the GN composition (COMGAS, 2014): CH_4 88,683 %, C_2H_6 5.844 %, C_3H_8 2.339 %, C_4H_{10} 0.771 %, C_5H_{12} 0.128 %, C_6H_{14} 0.025 %, N_2 0.594 % and CO_2 1.616 %. The R_{est} for this fuel is 6.202×10^{-2}.

4. DATA TREATMENT

A routine in LabView was implemented in order to perform the necessary data processing and treatment. The developed application consisted of three main sections: image calculations to obtain a temperature profile, accordingly to Eq. (7), correction factor determination, and average post-flame temperature calculation.

Eight .txt files containing the pixels luminous intensities were provided to the application as input. Those files represent the data obtained from the **S** and **P** polarizations for the air and natural gas situation, for both the focused beam and laser sheet experiments. It is worth to mention that each of those files represent the averaged data between 200 images taken for each scenario, and hold information from every pixel, resulting on a 1376×1040 matrix.

Those input files were read and converted into a 2D array structure inside LabView as a mean to make possible the execution of calculations element by element. Intensity graphs were utilized to display the data to the user; such structure can be described as a three-dimensional graph converted into a plane graph, making use of a color scale to represent the third dimension, which means that the result presented indicates both the x and y coordinates and represents the intensity (z-axis) following a color code. The intensity graphs were applied to show the user the input data; the intermediate calculated steps (as shown in Fig. 2) as well as the calculated temperatures (Fig. 3).
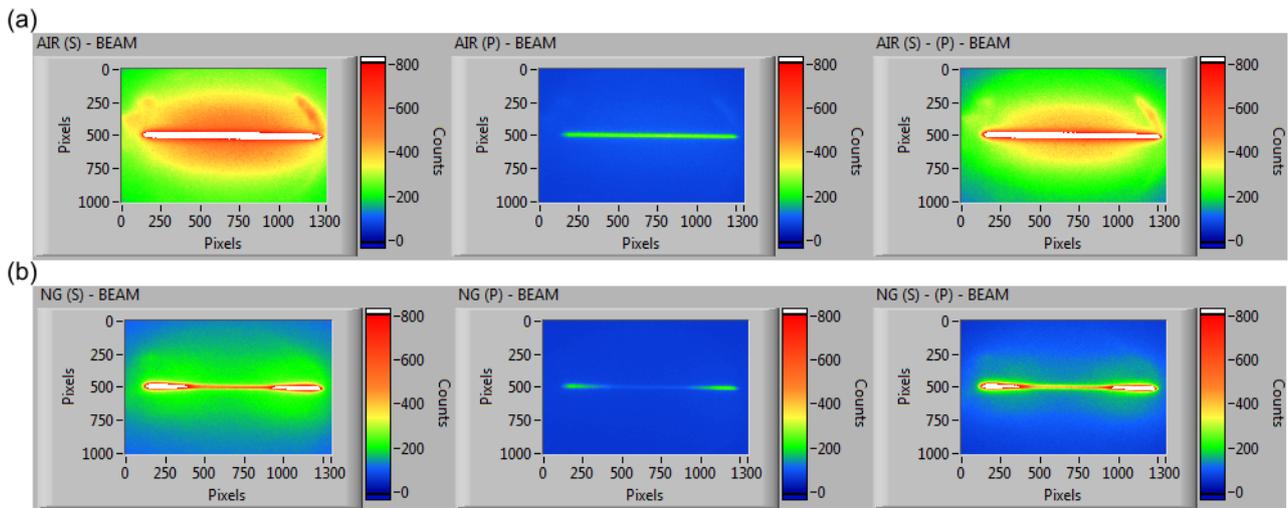

Figure 2. Built intensity graphs for the **S** and **P** polarizations as well as their subtraction for (a) air; (b) NG.
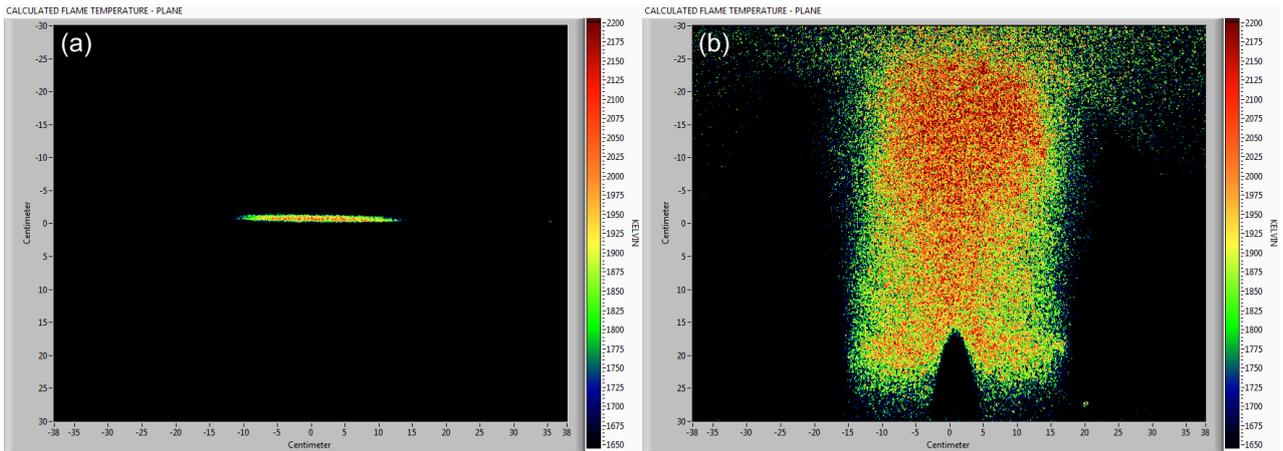
Figure 3. Calculated temperatures (a) focused laser (1D); (b) laser sheet (2D).

The temperature calculation not only rely on the input data files, but also require the user to provide the room temperature in which the experiment was conducted (T_{air}) and the average cross-sections for both the air and post-flame conditions (σ_{air} and $\sigma_{post\text{-}flame}$, respectively). Provided all that, the temperature was calculated for every pixel following Eq.(7).

During the experiments, a good background correction was not possible when employing the laser sheet (Fig. 4). In order to obtain reliable 2D-temperature distribution, the average temperature of a narrow high-confidence region of each flame was obtained with focused laser (1D, linear). In the LabView routine, the user, as indicated in Fig. 5, can specify this region in terms of lines and columns. The obtained average temperature is compared to the average temperature of the correspondent region obtained from the laser sheet experiment in the same flame, generating a specific correction factor for each case. The temperature distribution was then corrected by multiplying all the data by the obtained correction factor f, where:

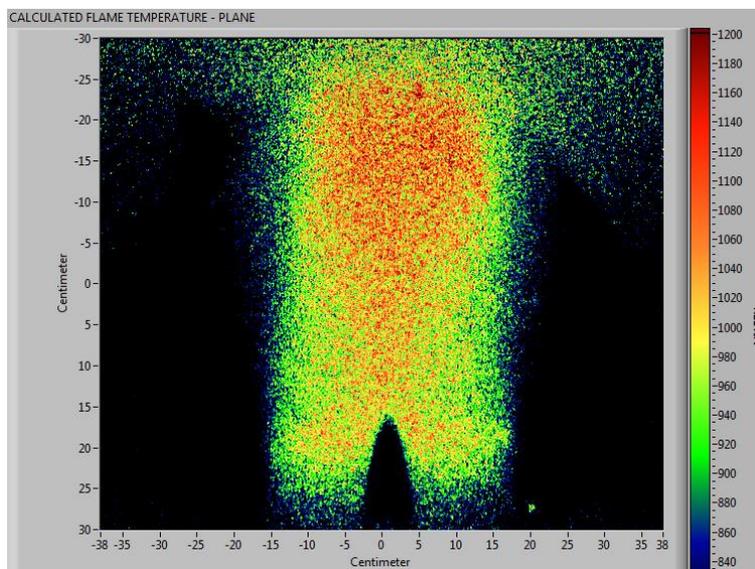$$T_{2D} = T_{1D}f \tag{7}$$

Figure 4. 2D-temperature distribution obtained by LRST in the $\phi = 1.05$ NG premixed flame without correction.

Similarly to the way done in the correction factor section, the user specifies the interest region to calculate the average post-flame temperature, resulting in a sub-array extraction (as displayed in Fig. 6) from which the temperature for every point is taken into account to calculate the average. The final temperature image than has its color scale adjusted in order to display the results more appropriately, generating a threshold to discard regions that are not interesting to the analysis nor present reliable results due to the unknown or different gas composition from that used to calculate de σ parameter.
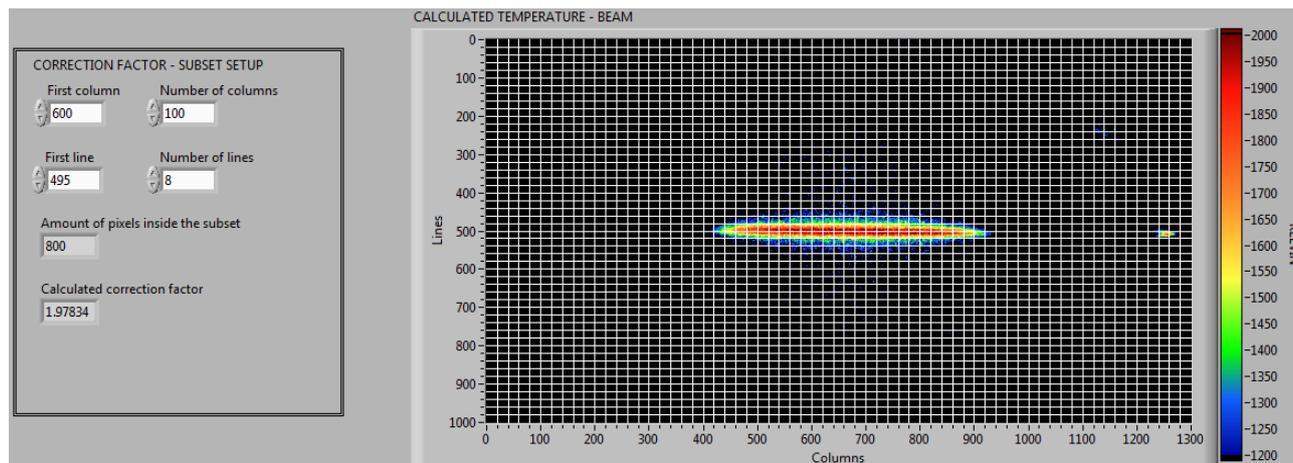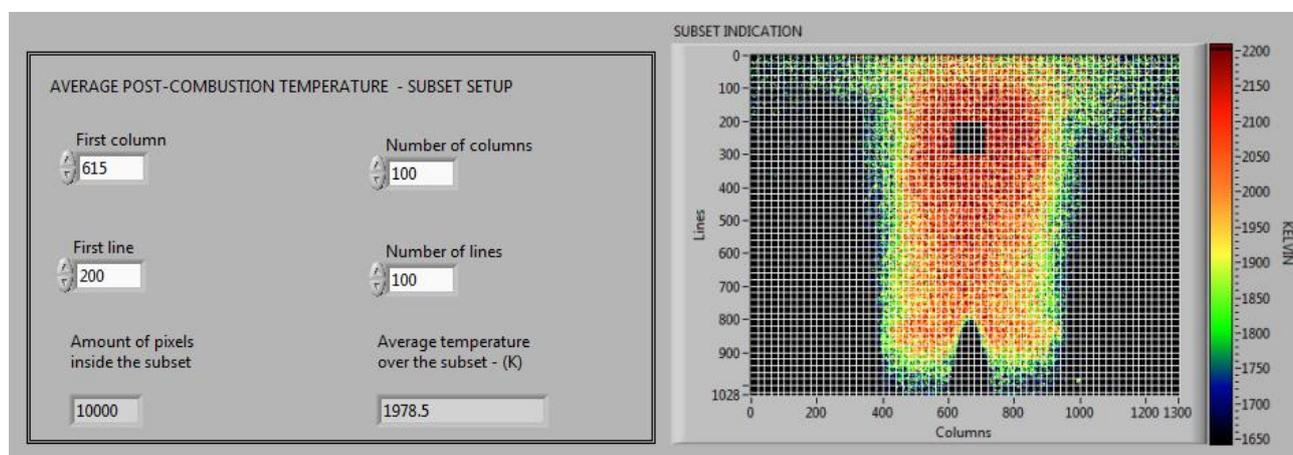
Figure 5. Region setup for correction factor calculation.

Figure 6. Region selection for average post-flame temperature determination.

5. RESULTS AND DISCUSSION

The values of σ_{eff} for post-flame regions ($\sigma_{post\text{-}flame}$) where calculated from the products obtained by Gaseq software, as shown in Tab. 1 (adiabatic flame, constant pressure). The Rayleigh cross sections for the constituents relative to N_2 for detection at 90° and perpendicular laser polarization are (LaVison, 2010): CO_2 2.30, H_2O 0.67, N_2 1.00, CO 1.28, O_2 0.89, H_2 0.22, CH_4 2.18. According Tab 1 data, $\sigma_{eff,\text{air}}$ is 0.9769.

Table 1. Post-flame composition obtained by the Gaseq software and effective Rayleigh cross sections relative to N_2 for detection at 90° and perpendicular laser polarization.

	Molar fraction, x_i		
	$\phi = 1.65$	$\phi = 1.05$	$\phi = 0.81$
CO_2	0.03705	0.08567	0.08138
H_2O	0.14911	0.18204	0.15076
N_2	0.60395	0.70286	0.72652
CO	0.10180	0.01705	6.49×10^{-4}
H_2	0.10797	0.00677	2.61×10^{-4}
O_2	5.47×10^{-9}	1.48×10^{-3}	0.03513
Σx_i	0.9999	0.9959	0.9947
$\sigma_{post\text{-}flame}$ [1]	0.9432	1.051	1.047

[1] normalized in relation to Σx_i.

The average temperatures determined with the LRST were very close for laser energies of 83 mJ and 40 mJ in the experiments realized with the focused laser beam, as can see observed in Fig. 7. However, with the use of laser energy of 4 mJ, the obtained average temperature presented a low precision due to the low signal-to-noise ratio, showing that the signal-to-noise ratio was not high enough to provide adequate correction of the background radiation. Lower energy levels are found when using the laser sheet (the total laser energy is distributed through the laser sheet). An increase in the number of images in each experiment can contribute to the increase in the signal-to-noise ratio, improving the accuracy of the results obtained when using lower laser energies.
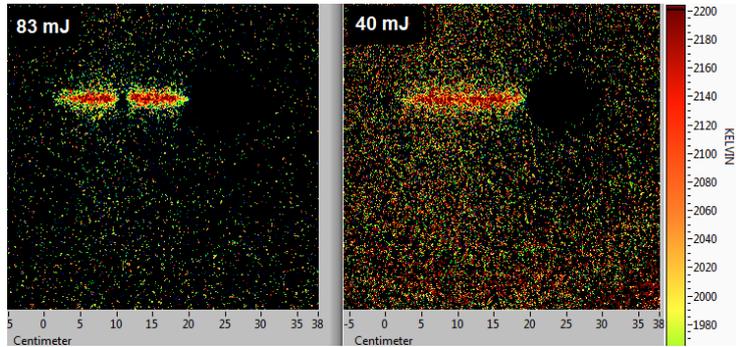

Figure 7. 1D-temperature of the NG flames, ϕ=1.05 with different incident laser energies.

Table 2 resumes the results obtained. Average post-flame temperatures where calculated after the corrections in the regions showed in Fig. 8.
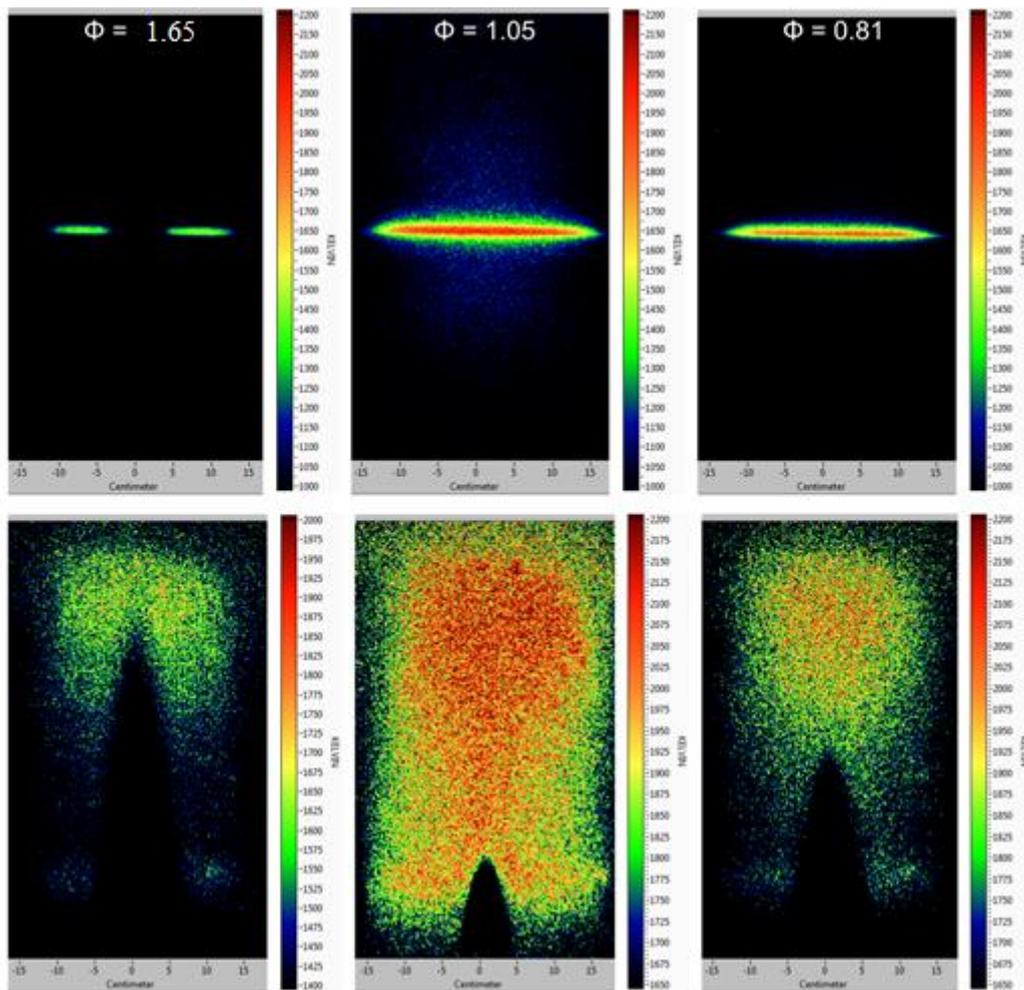

Figure 8. Temperature distribution throughout the NG flames. Up: 1D. Down: 2D.

The results obtained can also be improved by using more efficient masks to eliminate a greater amount of spurious light and employing greater laser energies.

Experimental temperatures obtained in this paper presented values up to 376 K (rich flame) lower than the adiabatic temperature calculated by the Gaseq program (Tab. 2). This can be due to significant heat losses to the environment for the low fuel flow used, which lead to a divergence from the adiabatic condition. Temperature values closer to adiabatic can be obtained by working with higher fuel flows (Sutton *et al*., 2006).

Table 2. Premixed NG flames conditions (NG mass flow: [0.0195±0.005] g/s, 298 K), average temperatures in the experiments 1D and 2D for f determination and average post-flame temperatures obtained through Rayleigh thermometry (see Fig. 6 for flame region considered).

$\phi\pm6\%$	$\dot{m}_{air}\pm0.005$ (g/s)	T_{adb} (Gaseq) (K)	$\sigma_{eff,post\text{-}flame}$[1]	In the same flame region,for f determination		T_{RT} post-flame (K)
				T_{RT} 2D (K)	T_{RT} 1D (K)	
1.65	0.190	1833	0.9432	584±35	1310±85	1457±85
1.05	0.300	2232	1.051	978±65	1845±116	1870±115
0.81	0.390	2010	1.047	771±51	1587±82	1736±82

(1) Effective Rayleigh cross section relative to N_2 for detection at 90º and perpendicular laser polarization

6. CONCLUSIONS

Rayleigh scattering thermometry using polarization strategy technique was adequate to obtain 2D-temperature distribution in the post-flame region in combustion environment if additional corrections to the background were made.

7. ACKNOWLEDGEMENTS

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