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Optical correction methods for a simultaneous LII and TC measurement of a low-sooting LPG diffusion flame

F. Naccarato, M. Potenza and A. de Risi

University of Lecce, Department of Engineering for Innovation
Via Monteroni - 73100 - Lecce
marco.potenza@unisalento.it

Abstract: Simultaneous measurements with the Two-Color emission and Laser-Induced-Incandescence techniques on a diffusion laminar LPG bunsen flame were performed. The acquired images were filtered, perspective corrected and processed via an on purpose made procedure in order to reduce the measuring error. For quantitative measurements of the soot volume fraction and temperature a tungsten lamp calibration method of LII and TC techniques was used. To correct the self-absorption and the laser attenuation through the flame, a correction method was developed by means of the laser extinction technique. Flame temperature distribution measured with the two-color method was validated with the corrected temperature measured with a fast thermocouple along the flame axis. Soot volume fraction were calculated with the two-color emission and LII and a good agreement was found. For quantitative measurements the influence of self-absorption and laser attenuation were found to be not negligible and an error of 12% was found as sum of the self-absorption and laser attenuation along the optical path.

Keywords: LII, Two-Color, Soot, LPG.

1. INTRODUCTION

Soot production mechanism was widely investigated with different techniques under various boundary conditions. Several steps forward were achieved to understand soot production from fuels because of the important implications on human health [1]. Most of the studies in the field of soot detection were carried out, by means of light emission and LII, using highly sooting hydrocarbons. In the present work a 2D analysis on soot volume fraction and temperature of a Liquefied Petroleum Gas (LPG) diffusion flame was performed with a common setup for Laser Induced Incandescence (LII) and Two-Color (TC) emission techniques. Such approach allowed to measure soot properties with two independent optical techniques, thus increasing the reliability and the accuracy of the measurements. Optical techniques assumed an important role because of the possibility to measure temperature, soot volume fraction and primary particles diameters as well as other important soot properties such as emissivity or refractive indexes. Light extinction has been widely used, because of its simple experimental setup and straight forward theoretical background, to measure some of the above mentioned properties [2]. The accuracy of the soot refractive indexes assumed a focal importance for volume fraction calculation. Smith and Shaddix [3] reviewed the history of soot refractive indexes values and they found out that some of the values used in literature were not supported by experimental evidences even though they were able to match experimental results. Light extinction, combined with scattering measurements, was used to calculate soot number density and particle size [4-5] or to validate the results of other optical techniques [6-7]. Laser Induced Incandescence (LII) could be used to measure soot properties such as volume fraction and primary diameters with spatial and temporal resolution. To make quantitative measurements, however LII needs to be calibrated by means of other independent techniques [8-9], such as laser extinction or scattering. Other approaches to calibrate LII signal have been proposed by Smallwood et al. [10,11], who developed a self calibrated procedure and by De Iuliis et al. [7,12] who suggested a multi-wavelengths analysis of LII soot emission signal, named two-color LII technique. The LII signal, as function of laser fluence, typically consists of three phases [13,14]: heating, graphitization and vaporization. The first one takes place up to 200 mJ/cm^2 and is characterized by a constant increase of LII signal with laser fluence. The second phase occurs for a laser fluence between200 mJ/cm^2 and 400 mJ/cm^2 and is characterized by a constant LII signal. The third phase appears when higher energy pulses are used (e.g. laser fluence>400 mJ/cm^2), thus soot particles vaporize and, due to the reduced radiative volume, the LII signal decreases. The third phase [12,15-17], should be avoided to make quantitative measurements using LII. Liu et al. [16] and Snelling et al. [18] carried out an experimental and numerical study and investigated the effects of soot properties on the LII signal and peak temperature after a 1064 nm 8 ns long laser pulse. They reported that the maximum laser fluence to avoid sublimation was 95 mJ/cm^2 and the correspondent soot particles temperature was about 3300 K. In these conditions temperature peak is not considerably affected by soot particles size and distribution. If laser fluence is above the defined low-fluence limit, sublimation heavily affects soot peak temperature and the initial cooling rate with the consequence that the peak temperature increases with particle diameter. Other studies [17,19] found that sublimation is negligible for a laser fluence of 200 mJ/cm^2 at a wavelength of 532 nm and 300 mJ/cm^2 at 1064 nm. Shultz et al. [15], by reviewing the state of the art in LII measurements, found that arising a fluence regime between 120 mJ/cm^2 and 200 mJ/cm^2 is reasonable condition to avoid soot sublimation and volume reduction, when laser pulses with 532 nm wavelength and a Gaussian beam profile are used. De Iuliis et al. [7,12,20], to carry out quantitative soot volume fraction measurement with the LII, used a laser fluence in the range of 350 mJ/cm^2 to 416 mJ/cm^2 with a 1064 nm 7 ns long laser pulse, rising a soot particles temperature peak of 4000 K . As pointed out in previous studies [17,21], a further effect, which cannot be neglected for quantitative measurements, regards the absorption of laser energy along the optical path through the flame. Hottel and Broughton [22], in 1932 developed the TC method to determine furnaces flame temperature. Several investigations were carried out by means of TC method on diesel combustion [23-27]. TC does not require an external light source as LII or laser extinction. Thus the application of TC results in a simpler experimental setup, especially useful when measurements have to be taken in situ. Spectral emissivity [24,28] represents a crucial element for a good determination of both temperature and soot concentration. Two different types of theoretical approach were adopted in order to derive an expression to be used for experimental use. From one side, spectral emissivity is deduced by means of the expression proposed by Hottel and Broughton [22,25,28,29] for spectral emissivity through the empirical determination of the α coefficient sometimes known as dispersion exponent, which depends on the optical properties of soot as particles size and fuel C/H ratio [30]. Hottel and Broughton calculated α on acetylene flame and they found the value of 1.39. Massoli and Di Stasio [30] carried out an exhaustive sensitivity analysis to estimate the influence of soot properties uncertainties on temperature and volume fraction measurements using TC method. To a quantitative use of TC measurement, the calibration process represents a critical step. The black-body emission of a tungsten lamp has been widely used as reference signal to calibrate TC experimental setups [31]. Svensson et al. [29] developed an innovative calibration technique, for the application of the TC method with a RGB (Red-Green-Blue) ICCD (Intensified Charge Coupled Device) camera. Multi-wavelength analysis of soot emission together with laser extinction technique were applied by De Iuliis et al. [6] to characterize the radial soot volume fraction and temperature distribution of an ethylene diffusion flame. Xu et al. [32] used a multi wavelength pyrometry together with soot volume fraction measurements by means of laser extinction method to analyze soot from different fuels flames. TC pyrometry was used by Berry et al. [33] to investigate pressurized laminar ethylene flames with 2D visualization. In several studies [6,33,35], optical tomography was applied to reconstruct the radial soot fraction volume using the Abel inversion. However as pointed out by Snelling et al. [36], soot emission measurement is not a line integral because of a self-absorption effect which attenuates the emission signal. Thus numerical methods were developed [37,38] to correct the self-absorption, which could reduce the measured soot volume fraction especially for the high sooting flames. In most of the studies the self-absorption effect is neglected under the hypothesis of optically-thin approximation. Daguse et al. [39] showed that optically-thin assumption is valid only with low stretch rate flame. This effect was also studied under several different combustion conditions and fuels [40-42]. As illustrated LII and TC are suitable and independent techniques to accurately measure soot properties for both high and low sooting flames. The present paper illustrates an experimental procedure to combine the two above mentioned techniques to make quantitative measure of soot concentration and primary diameters in flames

2. EXPERIMENTAL SETUP

To test the proposed approach for 2D soot properties measurements, a LPG diffusion flame from a bunsen with an inner diameter of 12 mm was used. A 25 % of C3 H8 and 75 % of C4 H10 LPG composition was used. To prevent flame instabilities a ceramic honeycomb with holes diameter of 0.5 mm was put inside of the burner and a constant air flow enclosed the flame. Two mass flow meters (Brooks Instruments 5850S/BC) were used to regulate the fuel and the co-annular air flow at a flow rate of 2.2 cc/s and 117 cc/s, respectively. The flame height was about 60 mm and the diameter at the base of the bunsen flame was 14 mm. Figure 1 shows a schematic of the experimental setup. An intensified Andor iStar, positioned in front of the burner was used to acquire images for LII and TC.

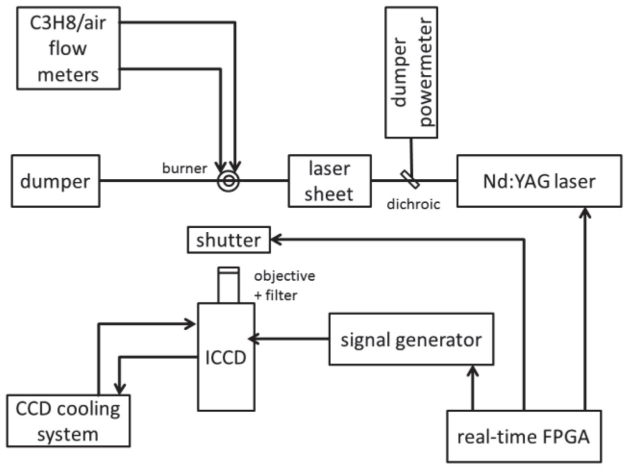

Figure 1 Schematic of the experimental setup used

The ICCD camera was equipped with an objective (fl=25mm and f/2.8), coupled alternatively with an interferential bandpass filters tuned at 488 nm or 635 nm with 10 nm of FWHM for both. Gate opening time was set to 10 ns. A Nd-YAG pulsed laser (Quanta Ray PIV 400) with 400 mJ of energy at 532 nm and a pulse duration of 8 ns was used for LII measurement. Laser beam was converted to a sheet of 0.45 mm width by a cylindrical lens assembly. A real time processor with an Field Programmable Gate Array (FPGA) on board provided the signal triggers for the laser, the shutter and the ICCD through the digital signal generator, which was activated by a trigger signal from the FPGA. A calibrated tungsten lamp was used in order to measure the ICCD camera calibration curves for the two selected wavelengths: λ_1=488 nm and λ_2=635 nm. An ordinary tungsten lamp by means of a monochromator Jobin-Yvone HR460 equipped with an intensified ICCD camera Jobin-Yvone UV18F, using the method proposed by Rosenkranz et al. [43] was characterized as function of temperature. The Larrabee [44] tungsten emissivity values were adopted. To validate TC temperature measurements in low sooting conditions, flame Temperatures along the flame axis were measured with a type S thermocouple. The used thermocouple was characterized by a junction diameter of 250 µm to assure a fast response and to reduce soot formation over the junction, without incurring in frequent thermocouple failures. These measurements were corrected for radiation losses with the junction emissivity and the heat transfer coefficient calculated with the assumption of spherical geometry of the junction. The value for the junction emissivity were taken from Bradley and Entwhistle [45]. The maximum uncertainty of the measurement was estimated in ±25K. Due to the low sooting LPG flame, a fluence value of 200 mJ/cm^2 was chosen to avoid soot sublimation and to increase the signal/noise ratio. If the laser sheet uniformly invested the flame, a descent should be expected after the initial phase, but the effect of the increased intensity of the laser sheet extremities produces a increment in the LII signal. Furthermore, even if pressure could locally varies with temperature, as found out by Bladh et al. [46], in conditions of low-fluence with a free atmospheric pressure flame the dependence of soot volume fraction and particles diameters on laser generated pressure fluctuations is negligible

3. THEORETICAL BACKGROUND

To calculate the radial emission for TC, the Abel inversion to the acquired images was applied [6,33,35] due to the cylindrical symmetry of the LPG flame. The Nestor-Olsen numerical method [47] was used to calculate the radial emission function. The intensity of spectral emission is described by the Planck's equation as a function of the wavelength and the temperature of the emitting black body.

The acquired intensity $I_a(\lambda, T)$ of a ICCD camera is related to the emitted power E_b at a certain temperature T with the characteristics of the optical system. Soot temperature and volume fraction were calculated from an equations system of temperature, wavelength and effective and apparent temperature of flame.

LII technique is based on the acquisition of the emission from soot particles heated at high temperature by a high energy laser pulse. The stimulated light emission of soot particles is characterized by a fast rising part having a duration of few nanoseconds, due to emission of the soot particles heated by the laser pulse, and a decreasing part of about 2000 ns, soot emission decreases because of particles cooling. The origin of the time scale is the onset of the 8 ns laser pulse. Soot volume fraction and particles diameters, are related to the LII signal in two different phases: LII signal is proportional to the soot volume fraction and the time decay of the LII signal is proportional to the particles dimension. Quantitative measurement of soot properties measurement through the LII technique requires a careful calibration of the acquired signal. To obtain the effective emitted power of the soot particles from the ICCD images, a characterization of the acquisition equipment is necessary [48]. The self-calibration method proposed by Smallwood et al. [11] based on the acquisition of the signal at two wavelengths was used in the present paper. To calibrate the acquisition system an ordinary tungsten lamp with steady known temperature was used. Soot volume fraction is related to soot concentration in steady state only where the LII signal curve reaches the maximum, before soot vaporization.

4. RESULTS AND DISCUSSION

To validate the TC temperature calculation, a comparison with temperature measured by fast thermocouple along the flame axis was performed. The flame temperature was measured at 5 heights from the bunsen outlet along the flame axis at 25 mm, 35 mm, 45 mm, 55 mm and 65 mm, respectively. TC flame temperatures were calculated as an average over a 10×10 pixel square portion of the temperature image. In Figure 2 the flame temperature profiles along the axis measured by means of the thermocouple and the temperature calculated with the TC are reported.

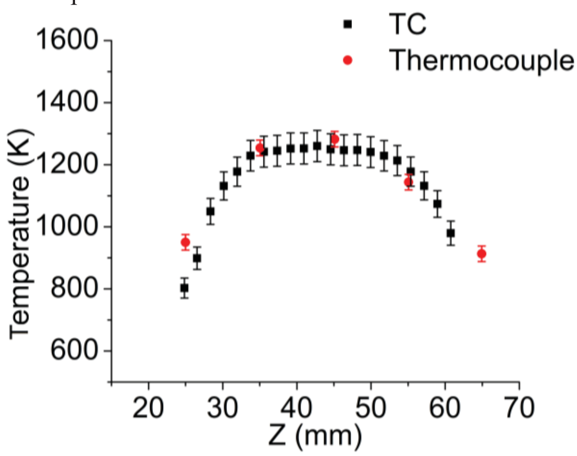

Figure 2 Comparison between the axial corrected temperature profile measured with thermocouple and temperatures calculated with TC method.

As can be observed there is a good agreement between the two profiles. Reported uncertainties in temperature calculation were estimated by taking in account the TC uncertainty and the signal spread over the acquired images. di Stasio and Massoli estimated the TC temperature measurement uncertainty, in the considered wavelength range (488 nm-635 nm), to be between about 15 K and 25 K in condition of low sooting environment using Chang and Charalampopoulos refractive indexes. Low-sooting environment is characterized by a product fv L<0.053 µm, where L is the length of the optical path. In the present investigation the maximum product fv L is about 0.0144 µm. The maximum spread error in signal images amounts at 5.32% which becomes in temperature to ±0.25% at 950 K and ±1.3% at 1350 K Uncertainties of the TC temperature measurements were less than 50K with the digitalization error of the CCD camera. In Figure 3 the 2D distribution of soot temperature and volume fraction as well as the axial profile and radial distribution at a height of 30 mm from the bunsen exit are presented.

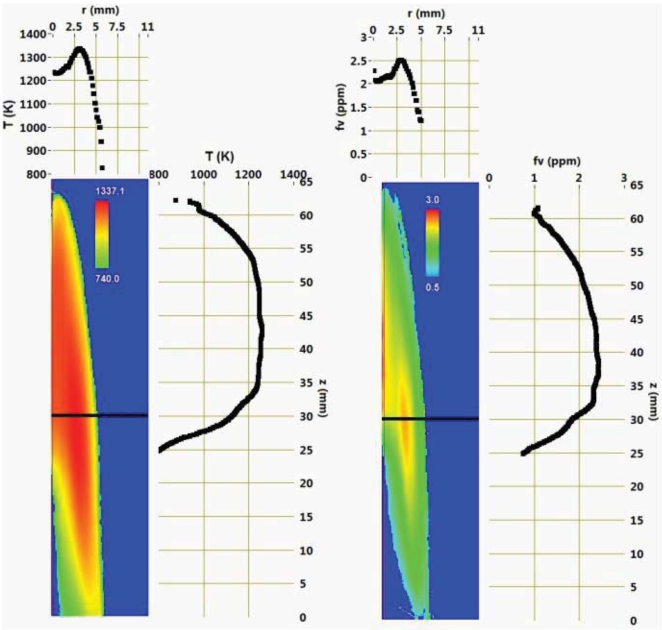

Figure 3 2D visualization of the soot temperature and on the right and axial profiles of temperature and on the left

It was not possible to measure temperature below 800 K because of the limit temperature (770 K) of the adopted calibration of the ICCD camera. Soot fv values are included in the range 0.2÷2.6 ppm. Both soot temperature and fv show their maximum value at a height of 30 mm and at about 3 mm from the axis. These zones cover the middle of flame between the core and the external part. More generally, these results confirm that the highest temperatures and fv are in the area around the exit of the fuel where the oxidation reactions take place. LII technique requires an additional discussion about the results in terms of soot fv. Two effects of soot absorption should be taken in account: the absorption of laser power through the flame path and the absorption of induced soot emission through the optical path in the direction of the camera objective. The first effect causes a decrease of the power transmitted to the soot particles along the path of the laser sheet through the flame and consequently a laser fluence loss (LFL). Figure 4 this effect is shown where a section of the LII signal at height of 30 mm from the bunsen outlet is reported. The curve with dark squares represents the normalized signal at 635 nm wavelength. This profile can be linearly interpolated by a straight line with the method of the least square residuals. If the LII emission was uniform the interpolating line should be horizontal, but, as can be noticed from Figure 4, the interpolating line is characterized by a negative slope which means that LII signal decreases according to laser attenuation along the optical path. This effect can be compensated by multiplying the original signal with the reversed interpolating line, hereafter called compensation line, reported in Figure 4. The behaviour described so far is repeatable at all heights of the flame. Laser sheet penetrates into the flame from the left and exits from the right side, where the signal intensities are sensible lower. After the correction LII signal becomes uniform along the radius, as expected by an axial-symmetric flame.

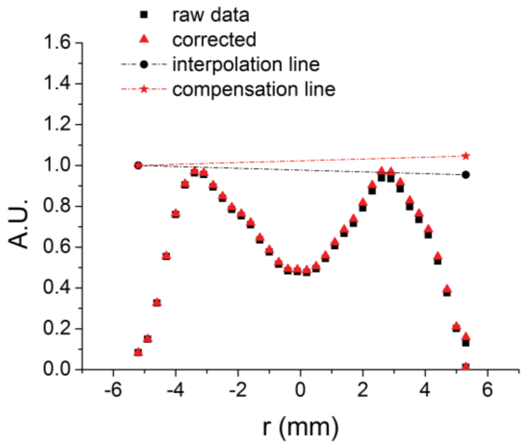

Figure 4 Comparison of the LFL compensated and uncompensated 635 nm

In Figure 5 the effect of the used correction procedure is shown where the non-compensated and the compensated laser fluence of the LII signal at the right contour of the flame are reported as a function of the Z axis. The effects of signal correction are more evident in the zones far from the bunsen exit where the greater volume fraction of soot and therefore the higher absorption of laser power is observed. The maximum correction was found to be around 3%.

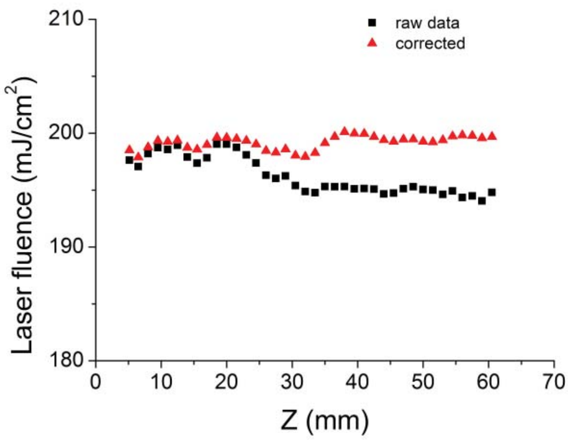

Figure 5 Comparison of the resulting laser fluence at the laser exit edge of the flame with the compensated one for LFL.

As can be noticed from Figure 5 after the compensation the laser fluence (red triangles) is more uniform and closer to the nominal value of 200 mJ/cm^2. As pointed out previously self-absorption (SA) can heavily affect soot light emission. In order to quantitative estimate the amount of radiative loss, an extinction measurement was performed by means of a He-Ne laser and the same CCD camera used for LII. A beam expander allowed to explore the entire flame and the narrow band-pass filter at 635 nm, was used to acquire the extincted signal. Transmittance information was used in order to correct the self-absorption of the LII signal through the flame. The highest value of transmittance in the flame area is about 16% thus, in the hypothesis of axial symmetry flame, a maximum reduction of LII signal intensity of about 8% is expected. To correct the fv calculation with the LII signal at 635 nm wavelength, the transmittance image was overlapped and aligned to the LII signal. Correction at 488 nm wavelength can be estimated under the hypothesis that the specific extinction coefficient for carbonaceous aggregates at 488 nm is about 20% more than at 635 nm [49-52] with carbon density and the flame geometry constant. Figure 6 reports the 635 nm LII signals comparison at 30 mm of flame height in case of uncorrected signal (black squares), after the only LFL (red triangles) and after the correction for LFL and SA (green stars).

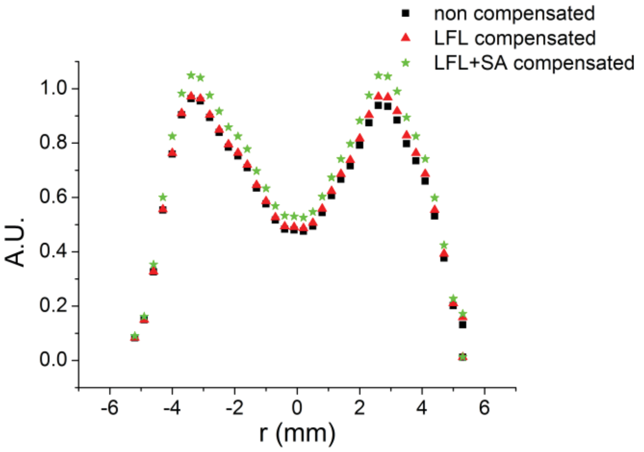

Figure 6 Comparison of LII signal at flame height of 30 mm for 635 nm wavelength of the raw signal (black), the LFL correction (red) and the LFL+SA correction.

A different nature characterizes the corrections made to the signal which depend on the geometry of the observed flame and on its type. The correction LFL is determined by the length of penetration of the laser within the flame and by the absorption characteristics of the flame. Therefore it can be applied only under conditions of axial symmetry. The correction SA instead assumes a stationary flame in time but not necessarily characterized by axial symmetry.

This temperature decay characterize the soot particles size, from the centre to the edges of the flame. In this condition and before the soot sublimation, it is correct to assume that the soot volume fraction is related to soot concentration at steady state [15]. In Figure 7 a comparison of f_v radial profile for both techniques at 3 heights along the flame axis is reported.

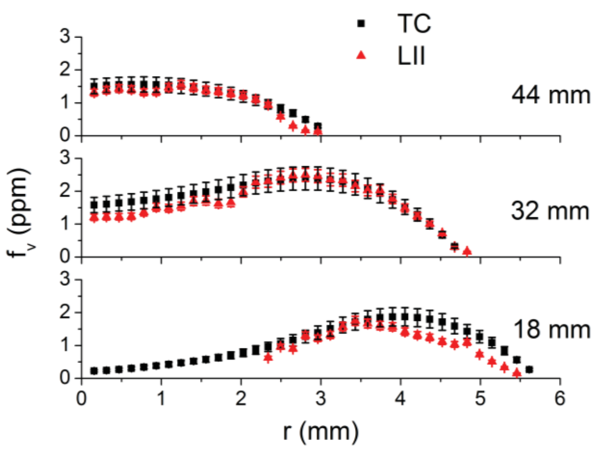

Figure 7 Soot volume fraction comparison between the TC and LII results along 4 different flame heights: 18 mm, 32 mm and 44 mm.

The largest discrepancies could be observed in this case. At 18 mm, at the edge of the flame because of the higher uncertainty in the calculate emissivity in condition of low sooting flame or cold flame regions [54]. Figure 8 reports the axial profile of f_v in case of TC and LII extracted from the 2D distributions. Also in this comparison the agreement between the two techniques is quite good.

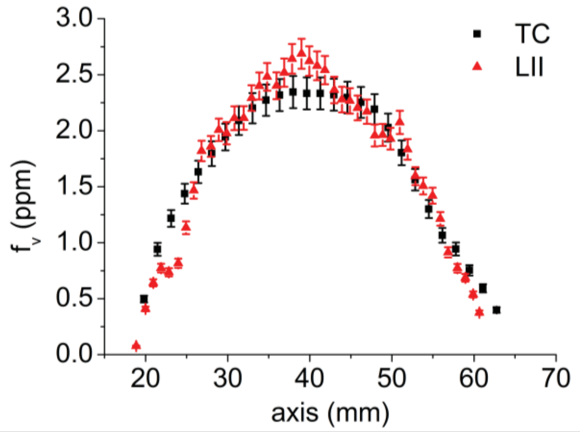

Figure 8 Soot volume fraction comparison between the TC and LII results along the flame axis.

5. CONCLUSIONS

An LPG bunsen flame was investigated with Two-Color technique and Laser-Induced-Incandescence for soot volume fraction and flame temperature measurement. The goal of the present study was to investigate the possibility to apply TC and LII to a LPG bunsen flame through an innovative imaging approach. Due to the low soot emission of the LPG flame several images were captured in different instants with 2 optical filters. Raw signal images were opportunely filtered and aligned in order to obtain a low noise level. Finally these averaged images were used to apply the TC and LII. Flame temperature calculated by means of the TC was compared with a thermocouple corrected measurements on the same LPG flame and a good agreement was found. An analysis on the laser sheet power loss through the flame allowed to develop a method to compensate the decreasing of LII signal along the flame radius. A laser extinction measurement was made in order to evaluate the self-absorption of the soot in the flame at 635 nm wavelength. LII signals images were further corrected for the laser power loss across the flame and for the self-absorption. It was found that these two factors can affect the temperature and fv results of about the 12% error, obtained by the sum of the self-absorption and the lase attenuation, which cannot be neglected in case of a quantitative measurement. Results from TC and LII were compared between each other and they agreed quite well.

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