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Assessment of Soot Emissions from Commercial Fuels

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***Abstract*— The aim of this work is analyse the soot emission in laminar diffusion flames produced from commercial fuels, which are stabilized on a burner representative of industrial applications. Methane, vehicular natural gas and liquid petroleum gas are considered as fuels. An experimental setup was constructed to implement the techniques of laser light extinction and laser-induced incandescence in order to provide instant information, in real time, about soot volume fraction. The liquid petroleum gas show higher values, circa 30 and 50%, than vehicular natural gas and methane, respectively. The correlation of the soot volume fraction values with flame radiation was investigated, which yields a coefficient of 0.92. The results will contribute to the database toward models validation and projects of combustion systems optimization, aiming to increase the combustion efficiency and soot emissions control.**

Index Terms—**Commercial fuels, laminar diffusion flames, and Soot emissions.**

I. INTRODUCTION

The soot emission has been the focus of many studies due to applications in industry and also by the prejudicial effects caused to the environment. Since the advent of optical techniques [1,2] the measurements accuracy has improved either the soot can be measured in high spatial and temporal resolutions, which allow to analyze the formation place and the behavior of soot production [3,4]. The presence of soot is of fundamental importance to the heat transfer in boilers and combustion chambers, contributing significantly to increased efficiency of these systems. In controversy, the inhaled soot may cause respiratory system diseases and even cancer. Moreover, another important aspect is the contribution to the greenhouse effect. The atmospheric pollution is strongly associated to the industry and automotive soot emissions, contributing considerable the global warming [5]. The concentrations of particles at which effects seem to occur are low by comparison with those to which many people are exposed in industrial workplaces. In this way, many studies are being done in order to investigate the soot formation [6,7] The soot produced by combustion in industrial process and by automobile vehicles using natural gas in urban regions in majority has sub-micron size. These particles are known to keep dispersed in the atmospheric for weeks. Also, the sunlight is absent leading to the non-photochemical degradation of the compounds. In urban zones, the particles are derived from combustion, which the carbon adsorbs chemicals substances onto the surface. These particles drift and pollute a wide area. The very fine particles penetrate into buildings, leading to a ambient with as much chemical particulate matter as is found in outdoor, in the same area [8]. The urban pollution cloud comprises very small acidic particles, in order of nanometer, which readily penetrate indoors and persist for long periods in air very small but chemically reactive particles. Studies of indoor air pollution in cities have shown that indoor air pollution levels often significantly exceed outdoor levels because of indoor sources such as fuel-burning appliances [9]. Regarding this and integrating the soot produced by indoor processes, as by cooking and warming into the houses, is clear to note that the exposure of people in urban centers is very high, whether in door or outdoor, and difficult to perform an accurate estimative. In other hand, soot is an important participate media in the thermal radiation exhibiting a fundamental role in the heat transfer within industrial combustion systems. Thus, the interest of measure the soot emissions are given by the importance of the process of soot production in flames, which enables to control the basic elements of hydrocarbon combustion [3]. There are several techniques able to measure the soot properties, each one have specifics skills and limitations. In this work an experimental setup is built to implement the techniques, is used laser light extinction (EXT) toward calibrate the results achieved by and laser induced incandescence (LII) [10]. The LII technique measurements are desired because provides high spatial resolution. In other hand, the approach of EXT technique is simple and the components are less expensive. These non-intrusive techniques provide instantaneous information, in real time of local soot volume fraction and soot particle size employed in combustion [11, 12]. This work aims to analyze the soot emission applied in laminar diffusion flames produced by commercial gases distributed in industry and houses to warm and cook, Liquefied Petroleum Gas (LPG) and to automobile industry, Natural Gas Vehicle (NGV). The Laminar diffusion flames of 80 mm visible height stabilized on a Burke-Schumann burner are considered, including using CH_4 in order to validate the measurements. Also a uncertainty estimative is performed, also the measurements are calibrated and validated using results available in the literature. A few works have been made measurements of soot levels in urban zones of developing countries. None of these, however, represent exactly the most widespread of potential exposures provided by commercial fuels emissions. The results of this work also contribute to the database for combustion systems optimization, aiming to assist projects to increase the energy efficiency and soot emission control.

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II. METHODOLOGY

The study is performed in laminar diffusion flames using a burner of configuration proposed by Burke-Schumann, in which are used two concentric tubes, the internal one with 4.7 mm and the external with 45.0 mm of diameter, in order to guaranty an axisymmetric laminar flame. The internal tube is responsible to the fuel stream and the external by the air stream in co flow. The volumetric flows are measured using a flow meter to air (AppliTech), scaled of 15-160 slpm, 2% of uncertainty, and also a flow meter to fuel (ASA), ranging from 0.15 to 1.4 slpm, 5% of uncertainty. The subject of this work is flames of 80 mm of visible height, considering CH_4, NGV or LPG as fuels. The volumetric flow of the fuels, V_{fuel}=0.20 l/min, and air V_{air}=20.00 l/min are monitored, also the velocities of these flow fields for each flame, U_{fuel} = 0.19 m/s, U_{air} = 0.10 m/s.

A. Laser light extinction technique

The approach used for calibration is applied to perform the laser light extinction technique, as proposed in [4], which consists to focus the laser beam in the flame and capture the light transmitted. The extinction of the light, i.e., the difference between the intensity after and before the laser beam passes through the flame is proportional to the mean soot volume fraction in the line of sight. As proposed by the Beer-Lambert law applied to soot analysis [4]. The flame thickness is measured performing a digital image processing, counting pixels with calibrated dimensions at different flames heights. The extinction coefficient, 7.8, was taken from the literature [13] and compensated to the laser wavelength used in this work. The results obtained from this application are mean and global, nevertheless, are usefulness to calibrate the qualitative results achieved by LII [4,14], which provide spatial resolution. The illumination in the extinction technique system consists of a wave continuum Argon ion laser of 514.5 nm of wavelength and light power of 2 W. The detection system is a photomultiplier tube (PMT), Hamamatsu, 931A.

B. Laser induced incandescence technique

The results of soot volume fraction, fv, obtained by LII measurements were taken using the assemblage, as proposed by [10]. The produced information by this system is local, i.e., provide results about soot concentration of the flame presenting high spatial resolution, circa 0.5 mm in this work. For this measurements is require a pulsed laser Nd:YAG, New Wave, with 532 nm of wavelength and 33 mJ per pulse in a cadence of 30 Hz in order to induce the incandescence of soot when the beam is focus on a small volume in the flame, transmitting an energy of about 0.7 J/cm2. The incandescence signal is captured by the PMT aided by a band-pass filter, which is centered in 650 nm, used to avoid the noise of the flame and background. The incandescence signal intensity is measured using an oscilloscope Tektronics, TDS 210, coupled in a computer.

C. Experimental approach

The measurements are taken spaced 10 mm each other, in the longitudinal direction, applying both techniques, with cadence of 10 Hz during 60 seconds totalizing 600 samples in order to get statistical confidence. The measurements development had shown many difficulties, requiring data treats and post processing. However, solutions were proposed to each problem. The flame instabilities were absent using a flow controller in order to avoid the effects on the signal detected. The flame light emission alters the light intensity captured by the sensors and also the flame oscillations at the top position mistakes the LII measurements results. Thus, a band-pass filter was used to increase the signal to noise ratio. Nevertheless, the signal intensity belongs small become difficult the measurements performed at low values regions, as found in the flame basis, mainly to methane fuel. The laser power supply varies produce intensity variations. In order to avoid this problem a large integration time was used to take the signals. Also, the presence of dust in the laboratory and the soot accumulation in the room along the experimental time are also important factors to increase the uncertainty.

D. Measurements uncertainty

The uncertainty in soot volume fraction measurements involves the following components as source to the laser light extinction technique, (i) laser light intensity, ±6%; (ii) soot extinction coefficient, ±8%; (iii) laser light wavelength, ±2%; (iv) flame thickness, ±1.5%. Thus, the total uncertainty in light extinction measurements is obtained by the propagation yielding circa ±10.5%. The measurement uncertainty in LII is estimated using the relative deviation from the results achieved by laser light extinction, which provide quantitative global values of fv. Toward determine this uncertainty was considered the methane flame, taken in account the discrepancy, which was estimated as roughly ±6%. A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

III. RESULTS AND DISCUSSIONS

The results achieved to the methane flames are compared with the literature [10], in order to validate the measurement method and extend for different fuels, NGV and LPG. The results present the soot volume fraction, fv, on each 10 mm height, h, at the longitudinal direction of the flame. A comparison between the results obtained in this work with the literature in order to validate the measurements shown results in good agreement. The maximum discrepancy observed was circa 20%. This value is in a satisfactory range regarding the measurement uncertainty and the complexity of the techniques. The mean results obtained using light extinction (EXT) and LII for different fuels are shown in the Fig. 1. The values of fv for LPG are higher for both cases and the CH4 are generally 50% smaller. The NGV exhibits roughly 20% less soot compared with LPG. In the Fig. 1 the squares

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presents the f_v values to LGP fuel flame, captured by LII technique, along the longitudinal direction upward the burner surface. The circles indicate the f_v results to LGP from light extinction measures, which were taken in order to calibrate the LII results. The triangles are the f_v values achieved from light extinction technique (up) to CH_4 and (down) NGV fuels.

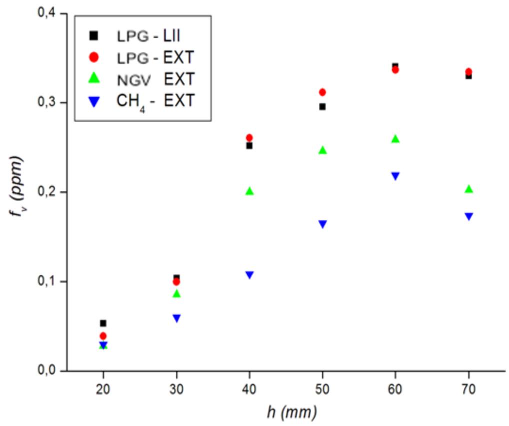

Fig 1. Results of fv to the flames height.

In the measurements at the flame extremities, both top and bottom were observed higher deviations due some difficulties by the instability at the flame top region and, also, the soot volume fraction low values in the bottom region. These values behavior also agrees with [14]. The precursor of the soot is formed in the flame base by the excess of fuel and reaches the maximum concentration where high temperature starts oxidize the aggregates and the soot concentration decreases. The results of f_v just above the burner, around 10 and 20 mm, where the precursors of soot are formed, exhibits very low values, around 0.01 ppm, i.e., 10 ppb, so that it is hard to measure accurately. In the other hand, the maximum values of f_v are found in the range from 40 to 60 mm in the longitudinal positions, presenting values about 0.3 ppm. Whereas, downstream this region is noted a smooth decrease of the f_v values, between 60 and 80 mm, circa 0.2. This behavior is due the oxidation of the agglomerates, as described by literature [14]. The behavior of the results obtained using LII in the LGP flame measurements agree with those from light extinction, including to the others fuels considered in this work. However, the LPG fuel shown higher values of f_v, followed by NGV and CH_4. It was expected, considering the carbon number in the chemical structure, that the sequence LPG, NGV and CH_4, respectively, presents the higher to low soot emissions. This happens because the LPG is formed by propane (C_3H_8) and butane (C_4H_{10}), while NGV is composed by approximately 80% of CH_4 and 20% of other hydrocarbons like ethane (C_2H_6), propane and butane. These variations of f_v along the flame height can be observed clearly in the **Fig. 2**, which shows the f_v of NGV flame on each 10 mm of longitudinal positions.

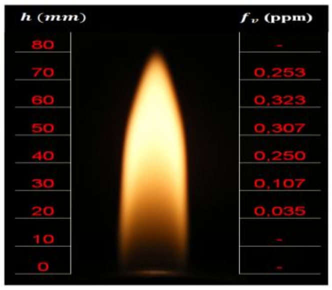

Fig 2. Distribution of f_v in to NGV flame radiation.

The light flame radiation captured with a CCD camera and the f_v values along the flame exhibit a noted proportionality, as expected due the majority of the radiation in the visible and near infrared bands is provided by the soot presence, regarding the black-body emission radiation law. Thus, the flame radiation is a function of f_v, as well as, the correlation coefficient between these results is found as 0.92. A radiometer was used to measure the flame radiation. This sensor is able to capture the flame radiation in the maximum wavelength of emission, between 1 and 5 μm, due the flame temperature reached around 1 000 K. Whereas, the CCD sensor captures the thermal flame radiation from visible to the beginning of the near infrared bands, from 0.3 to 1.6 μm. However, the results of flame radiation intensity captured with each sensor were compared, yielding a proportional behavior. Hence, the intensity distribution achieved in the flame imaging by CCD camera, as shown in the **Fig. 2** enable to create a three-dimensional reconstruction, as presented in the **Fig. 3**. The results of f_v from measurements and flame radiation correlation aid a tridimensional profile produced along the flame height (h) and flame thickness (x), as the flame radiation intensity and respective f_v (z) values, shown in **Fig. 3**.

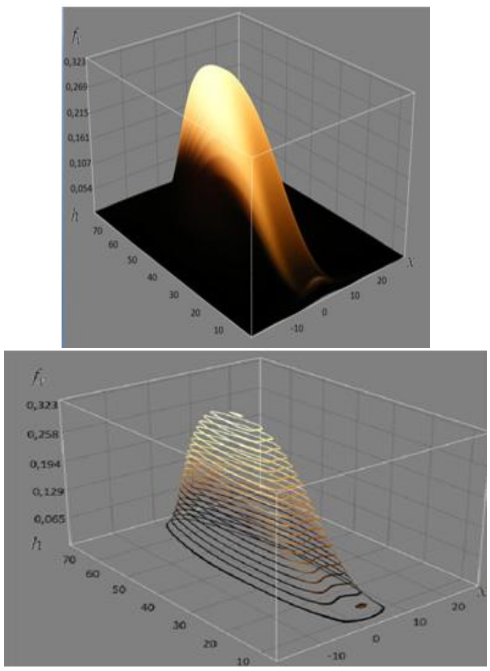

Fig 3. Radiation and f_v (top) and; isolines (bottom).

Furthermore, the LII technique was used to take local measures with enough spatial resolution in order to create transversal profiles at each height. Thus, the fit between f_v values and flame radiation emission tested are in agreement, regarding the measurement uncertainty attributed to this technique and the level of correlation. Thus, these images corroborates to the behavior achieved globally by the light extinction and, locally, with LII measurements.

IV. RESULTS AND DISCUSSIONS

The results obtained from techniques used to determine the soot volume fraction presented coherent results compared with the literature, in values and relation. Thus, the total uncertainty in light extinction measurements is obtained yielding circa ±10.5%. The measurement uncertainty in LII is estimated as roughly ±6%. The difficulties and uncertainty sources can be minimized using optical filters, stable supplies and flow controllers. The behavior of the LII data related to f_v as function of the flame height fitted with results of extinction results. The compatibility between the measurement methods was observed, allowing to perform global measurements with light extinction technique, leading to use LII in order to obtain spatial resolution and particle diameter results, from another fuels, in future works. Experimental results shown, as expected considering the number of carbon in the chemical structure, that the LPG have the higher f_v values, followed by NGV and CH_4, respectively, i.e., the higher to smaller soot emissions produced by the commercial fuels. The values of f_v for LPG are higher for both cases and the CH_4 are generally 50% smaller. The NGV exhibits roughly 20% less soot compared with LPG. The light flame radiation and the f_v values along the flame exhibit a noted proportionality, as expected in the range measured because the radiation is provided by the soot presence. Thus, the flame radiation is a function of f_v, as well as, the correlation coefficient between these results is found as 0.92. The behavior of the results obtained using LII flame measurements agree with light extinction to the commercial fuels. The correlation of the f_v values with the flame radiation was investigated using a CCD sensor, which was verified by a radiometer. Also, spatial measurements were performed using LII in order to map the f_v distribution around the flame.

V. ACKNOWLEDGEMENT

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