Study of the Evolution of Soot Formation using Laser-induced Incandescence

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Abstract: Soot particles usually cause respiratory diseases and other problems to human health. To prevent or at least reduces soot emissions it is necessary to know its formation mechanism. Laser-Induced Incandescence (LII) has been used to detect soot and its precursors, known as polycyclic aromatic hydrocarbons (PAHs), in diffusion flames. In this work, several mixtures of diesel/biodiesel blends were investigated using two laser wavelengths, at 532 nm, which excites both soot and PAHs, and at 1064 nm, which excites only soot. Thus, the difference of intensity between both LII signals provides the proportion of soot/PAHs in the irradiated regions of flames, and it can be associated to the evolution of soot formation along the flame.

1 INTRODUCTION

Diesel engines are currently the largest source of power generation in the planet, with employments in transportation, mining machinery and other areas. However, Diesel cycle is the major source of atmospheric pollutants, as soot and PAHs (polycyclic aromatic hydrocarbons) (Braun et al. 2003). Due to their small size, soot particles can penetrate into the alveoli of the lungs and may cause respiratory diseases (Lacava et al. 2010). Besides health problems, the presence of soot represents an important loss of energy in the thermodynamic cycle and its generation is related with the incomplete combustion of hydrocarbon fuels. Thus, the main interest in the soot reduction concerns both to human health and to environmental applications (Frenklach, 2002).

Soot are particles with size less than 0.1 µm, and they are formed in the flame front, i.e., the region in contact with the atmosphere air where burner reactions of hydrocarbon fuels take place and solid nuclei are generated. In this region, the complete oxidation of hydrocarbon fuels is also observed, mainly in poor fuel and high temperature flame conditions (Williams, 1976).

Alternative fuels, such as biodiesel, have been developed to reduce the emission of soot of the transportation sector. Biodiesel is made by the esterification of long-chain fatty acids derived from vegetable oils or animal fat (Mello et al, 2001). Biodiesel and its blends diesel/biodiesel present a high efficient combustion and can replace mineral diesel in compression ignition engines without significant changing of performance (Altin et al, 2001).

The soot detection can be carried out using several intrusive and non-intrusive techniques. One of the most efficient one is the Laser-Induced Incandescence (LII). LII is based on the temperature rise of soot particles above the background temperature by a high power incident laser. In this condition, the irradiated particles emit radiation like a blackbody, and the intensity of the continuous radiation is proportional to soot fraction of volume (Melton, 1984). When the laser pulse irradiates a soot particle, four physical-chemistry phenomena are observed in the particle (Figure 1): the absorption of the radiation by the particle; the heat conduction; the sublimation and, finally; the blackbody emission or incandescence. Since this method was first described, LII has been applied in studies concerned to the spatial and the temporal qualitative distribution of soot, the quantitative determination of the soot fraction volume (Shadix and Smith, 1996) and in the size evaluation of primary particles (Mewes and Seitzman, 1997).

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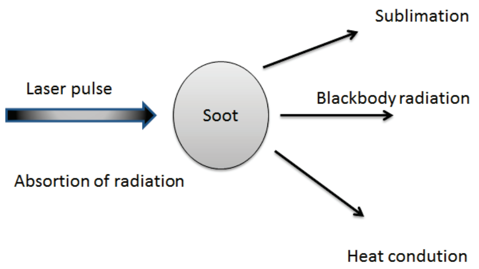

Figure 1: Physical-chemistry processes observed when a high power pulse irradiates a soot particle.

The aim of this work is to study the soot formation in blends with several proportions of biodiesel/diesel using LII as diagnostic non-intrusive technique. The biodiesel flames were irradiated by laser wavelengths of the 532 nm and 1064 nm. From the comparison between both LII intensities, the proportion between the productions of soot and PAHs can be estimated (Vander Wal, 1996).

2 EXPERIMENT

2.1 Burner and Fuels

The burner used in this work is identical to described in a previous work (Tran et al, 2012). A scheme of it is shown in Figure 2. Several blends of diesel/biodiesel were used as fuel, with an increment of amounts (v/v) of biodiesel to the pure diesel, identified in this work as B0, of 5% (B5), 10% (B10), 20% (B20) and 50% (B50). The biodiesel used in the experiments was provided by the company Fertibom, and was made from bovine fat (10%) and vegetable oil (90%).

2.2 LII Excitation and Detection

Basically, the LII diagnostic is divided in two steps: the excitation of the soot and the detection of the incandescence signal. The excitation process depends of the wavelength and the fluency of the incident laser. The radiation absorption is higher for smaller laser wavelengths. However, for ultraviolet lasers, the soot fluorescence, and mainly of the PAHs fluorescence, can also take place as an interference signal. Thus, the use of higher laser wavelengths is recommended to avoid these spectral interferences. However, the 532 nm laser also produces a remarkable fluorescence in a large class of PAHs. (Vander Wal, 2009)

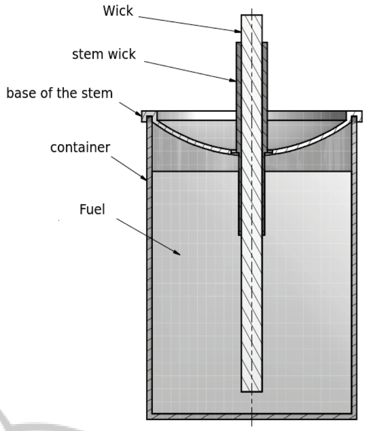

Figure 2: Wick fed lamp: diffusion flames generator.

The LII signal rises almost linearly with laser energy. As energy increase, the system temperatures also increase, and at about 4000 K, the vaporization of irradiated species starts. Above this threshold, LII signal remains quite constant. Figure 3 shows the results of LII signal measurements from a pure diesel flame (B0) versus the pulse energy of the both 532 and 1064 nm incident laser used in this work. One can observes that for both lasers, LII signal increases up to 14 mJ and, over this value, the collected signal becomes slightly constant (Vander Wal, 1994). This means that the LII signal does not suffer interference of small variations from the incident laser. All LII measurements in this work were carried out above this laser energy to guarantee that the LII measures were dependent only of the soot fraction volume.

2.3 Experimental Arrangement

Figure 4 shows a scheme of the experimental arrangement used in this work. A pulsed Nd:YAG operating at first and second harmonic, 1064 and 532 nm, was used as energy source. These wavelengths excite, respectively, the soot particles and the soot plus the polycyclic aromatic hydrocarbons existing on the soot surface. Laser beams were concentrated in the flames by using a lenses system, which increased the laser fluency. The LII signal was collected by lenses into a monochomator to avoid spectral interferences. The LII signal was detected by photomultiplier tube and, finally, recorded by a digital oscilloscope.

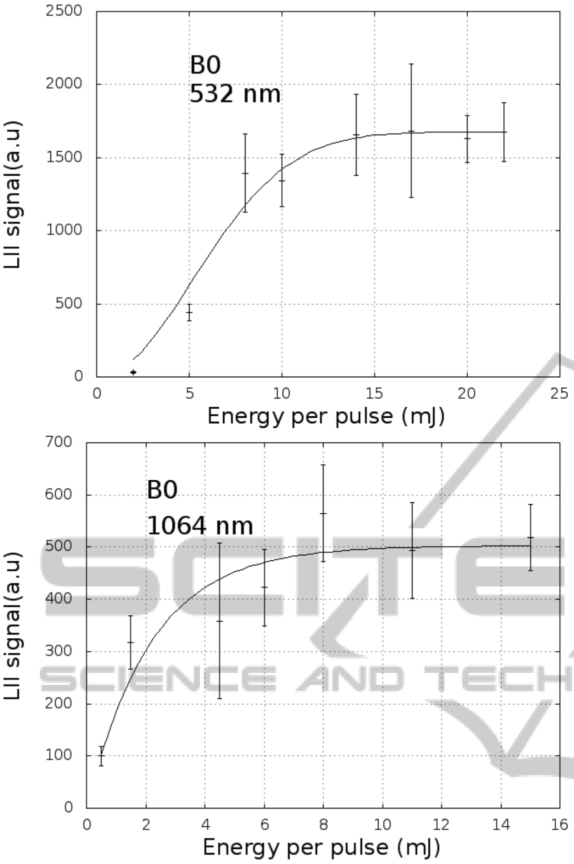

Figure 3: The behavior of LII signal versus the incident laser energy in pure diesel flames (B0).

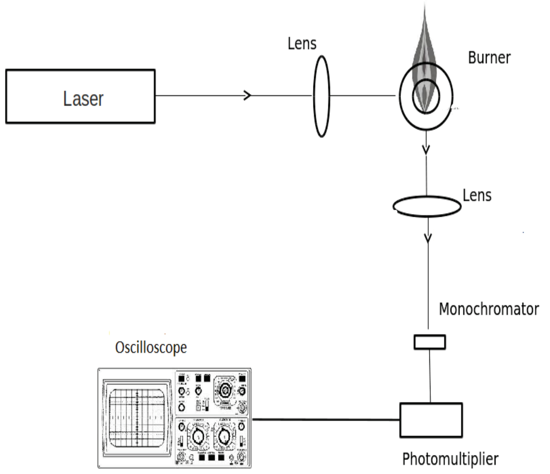

Figure 4: Experimental set up of Laser-induced incandescence.

2.4 Description of the Experiment

The LII signal was collected from two different regions of the flames: at 80 mm and at 260 mm above the top of burner. The first one corresponds, according to the literature, to the region where starts the soot formation, while the second one concerns to the completion of this process (Gaydon, 1957). All LII intensities were normalized using as reference the values obtained at 260 mm for each flame, because, in thesis, these values are the highest possible of the LII signal. Thus, this procedure allowed the comparison between the results of 1064 and 532 nm lasers and, as consequence, a qualitative estimation of the proportion of soot/PHAs in the flames. The LII signals showed in this work were calculated from an average of at least 500 measurements. This applied statistics supported the reliability of the acquired data.

3 RESULTS

3.1 Mapping of Soot/Pahs in the Flame

Figure 5 shows a picture of a B0 flame and a representation of the investigated flame heights (dashed lines). In diffusion flames like this, a strong yellow emission is observed due to the presence of soot (Gaydon, 1957). Beside the flame picture, one can observed a graph of the LII intensities along the horizontal axis of the flame for each height. At 0.8 mm, LII signal showed a distribution with two maxima separated by a valley. Both ones corresponds to the yellow soot region, while the valley is due to the dark poor soot region localized in the center of the flame. At 260 mm, however, only one maximum is observed, and it is associated to the strong yellow emission in the top of the flame.

3.2 Comparison between 1064 and 532 Nm Data

Figure 6 shows an overall view of the LII distribution of the investigated flames. It can be observed that the LII signal obtained using 532 nm laser is higher than 1064 nm for all studied blends. This behaviour can be atributed to the amount of PAHs on the soot's surface. According to the literature (Gaydon, 1957), at the bottom of diffusion flames, which corresponds to the height of 80 mm above the burner in this work, the process of soot particles formation is still in progress, and, therefore, the existence of a certain amount of precursors on the soot's surface is expected.

Thus, the 532 nm LII intensity profile at the 80 mm corresponds to the convolution of the soot and

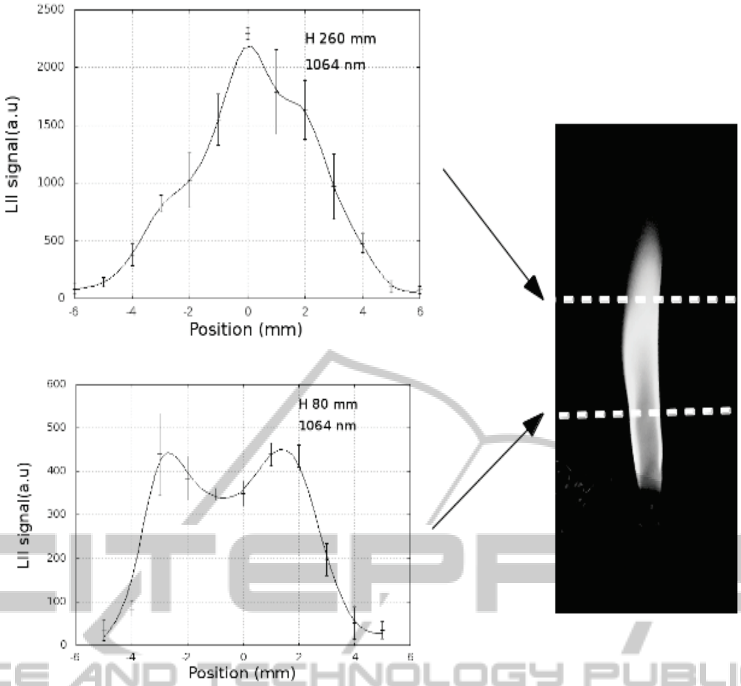

Figure 5: The soot distribution in a diesel diffusion flame at heights of 80mm and 260 mm above the burner (dashed lines).

PAH signals, while the 1064 nm intensity is only due to the soot presence. The results in Figure 6 showed that the difference between the LII intensities of both laser wavelengths increases with the rise of the biodiesel fraction. This rise is initially small from B0 to B5 blends, but the increment ratio systematically enlarges from the B5 to the B20. However, the LII intensities of the B50 blend are just slightly higher than observed for B20 blends. This suggests that the adding of biodiesel to the pure diesel fuel causes a delay in the soot formation process. To confirm this inference, a more complete mapping of the flames must be done.

4 CONCLUSIONS

The aim of this paper was to investigate the relative amount of precursors on the soot's surface in the bottom of flames of diesel/biodiesel blends for estimate the evolution of soot formation using the technique of Laser-Induced Incandescence. The results showed that the LII technique is efficient to evaluate the spatial distribution of soot in a diffusion flame. For all fuels investigated, B0, B5, B10, B20 and B50, the LII signal intensities obtained using 532 nm laser were higher than the obtained with 1064 nm laser. This behaviour is according to the former studies of flame literature. At the bottom of flames (80 mm), soot is still in formation process. The results also showed the addition of biodiesel to the diesel blends causes a delay in the soot formation process.

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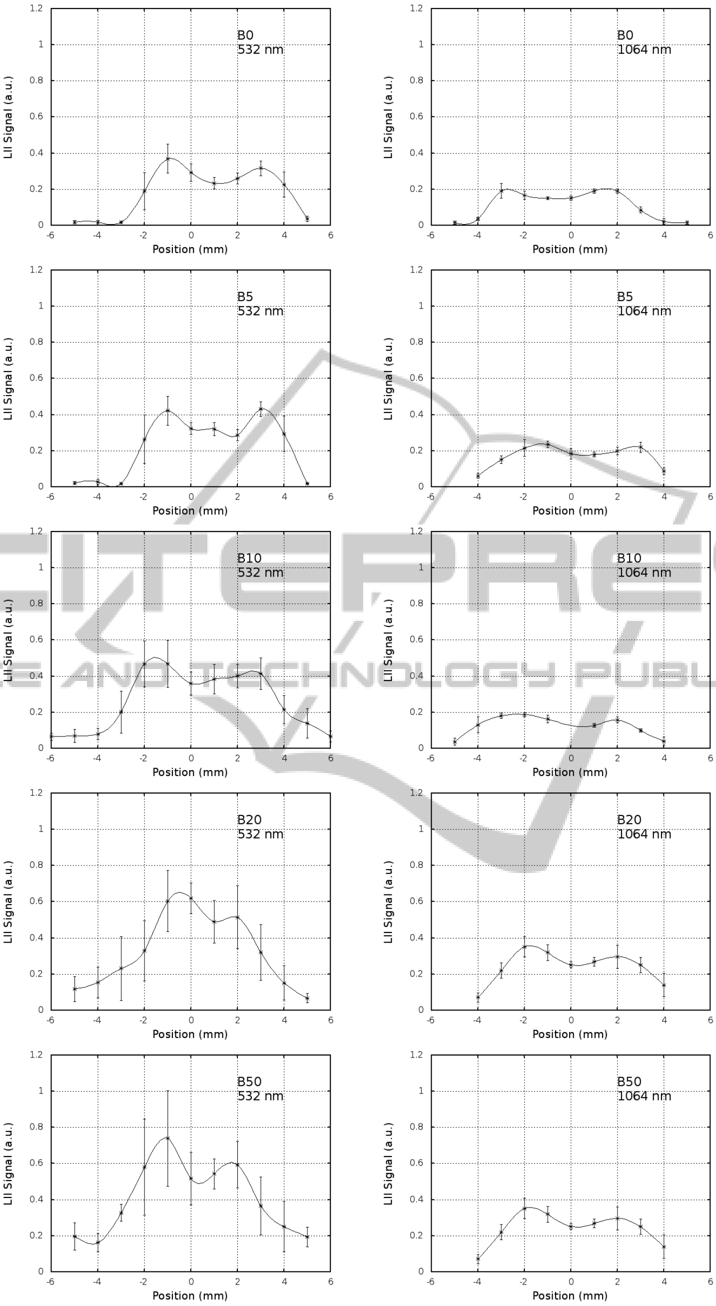

Figure 6: The LII signal intensities for the 532 nm and the 1064 nm lasers for all fuels investigated.

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