Soot formation in Partially Premixed Flames over a Wide Range of Premixedness

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Abstract

The process of soot formation in partially premixed flames was investigated in a co-annular burner with overall velocity and equivalence ratio maintained constant. The fuel content in the core stream was varied from 100 % of the total fuel to 10%, to span the regimes of fully diffusion to fully premixed flame, while maintaining the overall equivalence ratio as 0.8. During this progression, it was observed that the peak soot region moved inwards, the onset of soot luminosity zone moved more downstream, and the temperature decreased. For 40% case, it was observed that the rich and lean premixed flame branches appear and that marks the onset of receding soot luminosity zone from the burner lip. Beyond this case, the soot zone was in between the rich premixed flame and the diffusion flame. The onset of luminous zone is pushed downstream as the rich premixed flame develops into becoming a cone. The luminous zone disappears when the rich premixed flame assumes a full conical shape. Thus the soot development process in partial premixed flame regime, requires heated fuel with less air, with high temperatures, along with a gradient in fuel concentration.

Introduction

Unburnt hydrocarbons are the source of soot in the world today. Soot has many hazardous effects on living organisms including many cardiovascular dysfunctions. Soot is one of the predominant particulate matter pollutants from combustion systems in the world. Thus it is important to understand the physics of formation of soot in various combustion systems. This work in particular focuses on soot formation in laminar partially premixed flames.

Guo *et al.*[1] studied ethylene/air co-flow diffusion laminar flames at atmospheric and higher pressures. Soot volume fraction was measured using the two-dimensional line-of-sight light attenuation method. They reported that the peak soot volume fraction position shifts towards the centerline with increase in pressure. Liu *et al.*[2] observed significant reduction in flame height when the central air jet flow rates were increased for sooting characteristics in a co-flow methane/air diffusion flames in a triple port burner. Reduction in luminosity of the glowing soot to almost pure light blue indicated the depletion of soot. It was also reported that the formation of the inner inverse diffusion flame significantly increases the temperature along the flame centerline, thereby facilitating and enhancing soot formation. Goldstein Jr. *et al.*[3] studied the effect of external air diffusion on soot formation. They observed that when secondary air was introduced into the flame, it increased premixing and soot formation was reduced. Bladh *et al.*[4] described a methodology to locate soot using two-colour LII upto the limit of natural and induced incandescence, and thereafter, broadband emission was used to detect soot. The latter method is also used in this work.

This paper focuses on where the soot formation starts in a co-flow partially premixed flames using flame imaging and LII. Laser extinction [5] was used to find out the line of sight averaged soot volume fraction for different premixedness cases.

Experimental Setup

The co-flow burner used here (see figure 1) has an inner jet whose diameter was 10 mm and the inner tube extended downstream compared to the outer jet exit by 10mm. The outer tube had a diameter of 33 mm, and it extended into a Quartz tube of same inner diameter and the glass tube extended 100 mm after the inner jet lip. There were honey combs for straightening the flow, just upstream of both the jet exits. The fuel and air flow rates to the inner and outer streams were controllable independently. Each of these streams had a settling chamber for itself, before the burner.

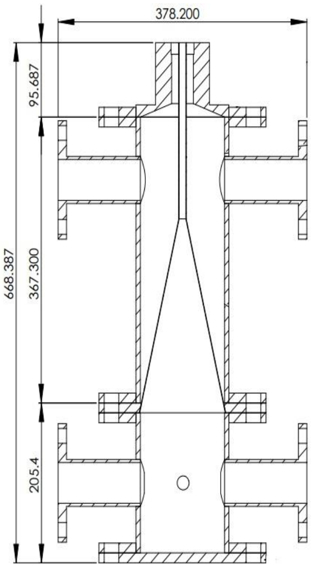

Fig. 1. Burner drawing without the Quartz tube being shown.

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The overall fuel and air flow rates were kept constant along with the average velocities in the two streams at 1.83 m/s. The flow was very laminar and the Reynolds number of the flow was 3700 based on the outer diameter. The flow was found to be very steady and repeatable for all the flow situations used in this study. However, when the equivalence ratios were very lean and almost fully premixed flame was present, there were some oscillations in the burner near the outer tube. Ethylene was used as fuel in this study in order to have molecular weight very close to that of air. The overall equivalence ratio was set at 0.8.

The schematic of the diagnostic setup that was used is shown in figure 2. LII was done with a frequency doubled Nd:YAG laser (Quantel YG 981+). The sheet laser sheet dimensions were 100 mm in width and 0.5 mm in thickness. The laser fluence was kept at 0.23 J/cm^2. A Nikkor 50 mm f/1.8 lens mounted on an ICCD (Princeton Instruments PIMax) was used to capture LII signal through a 450 nm (Edmund Optics make, FWHM 10 nm) interference filter. The exposure of the ICCD was set 100 ns to eliminate any chemiluminescence in the process.

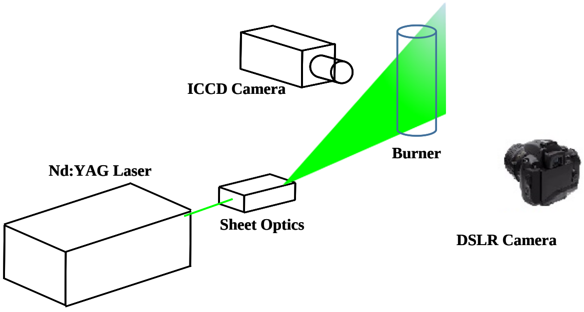

Fig. 2. Laser/Imaging Diagnostic Layout.

A total of 70 instances were taken and temporally averaged to get the time averaged LII data. A photo detector (Thorlabs Inc. make) was used to take into account the laser shot to shot variation. The images were then corrected for that. The laser and ICCD were in accordance with Mulla et.al. [6]. Instantaneous flame imaging was done using a Nikon D3200 DSLR camera mounted with the same lens as mentioned above. The ISO was set to 200 and correct exposure was maintained throughout the study.

Line of sight integrated laser extinction experiment was also carried out at a height of 80 mm above the burner lip. A photodiode recorded the transmitted intensity data at 1 kHz. Another photo detector was used to monitor any intensity fluctuations of the red He – Ne laser (628.3 nm). This was done by splitting up the laser beam into two parts, sending one to the flame and the other to the reference photo detector. Data Acquisition system was used for the inputs of ICCD, laser shot to shot photo detector and CW laser photo detector. The schematic can be seen in Figure 3. Care was taken to eliminate the soot emission signal from the extinction data by background and flame emission signal corrections.

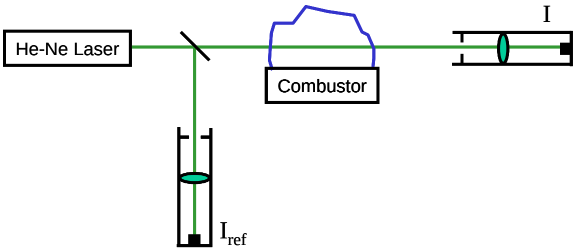

Fig. 3. Schematic of photo detector setup.

Results and Discussions

Initially only fuel was sent from the core and only air through the annulus, giving the classical diffusion flame. Fuel from the core was then decreased and fuel to the annular stream was increased, while the opposite was done for the air flow rates to maintain equal velocities in both streams. This gives variation of equivalence ratios of each of the streams making the outer stream more fuel rich and inner stream fuel lean. This brings the purely diffusion flame progressively closer to premixed flame. When 10% of the fuel from the inner tube is rerouted to the outer tube, the system becomes fully premixed with same equivalence ratio for both the streams. The operational conditions were set as 100% to 10% fuel in the inner stream in steps of 10% of fuel in the core jet.

Figure 4(a) shows the flame images for various fractions of fuel in the core stream. The left most case corresponds to a purely diffusion flame, while the right most flame is very close to fully premixed flame. The luminosity of the flame in the three left most images were decreased by adjusting the exposure so that the DSLR camera does not saturate. All the others had the same exposure settings. Soot glows with a bright yellow color emitting all wavelengths. This can be seen in the first few images of Figure 4(a).

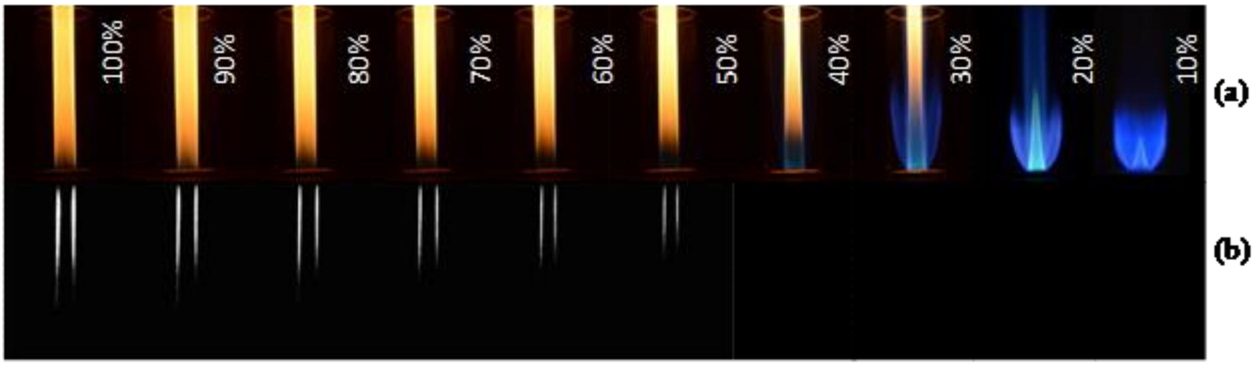

Fig. 4. (a) Flame images and (b) Time averaged LII signal, .for various core fuel % of total fuel flow rate, keeping the overall equivalence ratio and velocity constant. The cases illustrate progress from diffusion to premixed flame from left to right.

It is seen that the soot radiation is very dominant from the base of the flame upto 70% case, and the soot luminosity decreases near the base from 60% to 40% cases. The yellow soot luminosity region starts to move up when the conditions progress towards more premixed. When the flame becomes more premixed, the flame at the mixing layer does not have strong species gradients and thus the rates of transport will be weaker, decreasing the strength of the flame. This observation suggests that the formation of soot is delayed when the temperature is not very high.

It is also seen that the blue chemiluminescence emission is seen only when the soot emission is weaker. The inner and outer premixed flame branches begin to appear at 40% case, and become stronger as more fuel rerouted to the outer stream. The first lean flame is observed at an outer equivalence ratio of 0.52 and inner equivalence ratio of 3.92. The soot luminosity region appears to have moved significantly downstream from 40% to 30% case and the luminous zone vanishes in 20% case.

Figure 4(b) shows the time averaged LII signals for the same cases. The images show that the LII signal is much weaker than the soot luminosity, and thus there is no signal from the lower parts of the flame. It is clear from the images that the peak location of soot is shifting inwards with more premixing. This is seen by the gap between the two parallel lines decreasing with premixing. This observation is documented in literature as well.

LII signal is zero for 40% case when the soot luminosity still suggests presence of soot in the flame. These images suggest that the size of the soot particles decrease when premixedness increases. The soot size decreases below the detection limit for the LII setup used, for less than 40% cases. This observation may suggest that the soot formation is hindered significantly by the appearance of the premixed branches around the diffusion flame.

It should be noted that LII signals are absent beyond 50% premixing shown in Figure 4(b). Lowering the laser fluence was also attempted to track soot beyond the above mentioned limit, but it failed to give any signal. It is speculated that the size distribution of the soot particles are so small, that they get vaporized in their process of getting heated by the laser.

It is also seen from the images, on careful study, that the soot formation is on the post rich-premixed-flame region. While this region can have higher temperatures, it will have fuel molecules disintegrated into smaller molecules, which are products of rich combustion. Thus there is some optimum condition required for soot formation in partially premixed flames.

Figure 4(a) shows there is a significant drop in sooting levels from 30% to 20%. Thus, in this range, flame images were taken in steps of 2.5% as shown in Figure 5. It is evident from these images that the soot formation zone is clearly between the rich flame branch and the diffusion flame branch. The beginning of the yellow zone shifts upwards significantly from 30% to 25% and there is no yellow zone below 25% fuel (to core flow) case. It is also clear that after 25% case, the inner premixed flame closes on the top to become a conical flame, which burns all the rich mixtures from the inner tube to give fuel rich products.

Fig. 5. Flame images from 30% to 20%.

It can also be observed that the color of the luminous zone is going from bright yellow to pale yellow to orange, suggesting that the black body emitters are now at lower temperatures. Below 255, the three branches, viz., rich, diffusion and lean flames, are clearly visible in all cases. Thus these observations suggest that soot formation requires high temperature, along with less oxidizer containing zone, and probably sharp gradients on fuel concentrations.

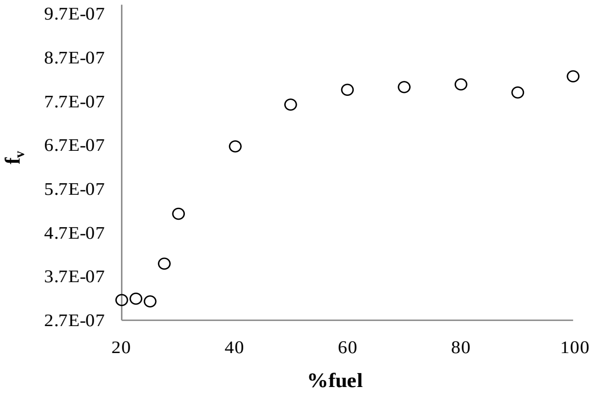

Fig. 6. Soot Volume Fraction vs. Fuel Percentage in inner stream

A plot of soot volume fraction obtained from the laser extinction method is presented in figure 6. Soot volume fraction, 'f_v', is in ppm. The plot shows the dependency of line of sight averaged soot volume fraction with percentage of total fuel in the inner stream. The plot shows an almost constant soot fraction for diffusion cases and soot fraction dropping fast below 50% fuel conditions. At 25% fuel case, the soot volume fraction is minimal because the soot luminous region in the flame images is above the measurement line for laser extinction.

The soot data from extinction measurement is consistent with that of LII upto 50% case. The luminosity of the flame at pure diffusion is the highest and the luminosity decreased with decreasing fuel content in the core. This is not reflected in the soot volume fraction. Thus it suggests that the luminosity is related to higher temperatures of the particles in more diffusion like flames.

There are some inconsistencies in interpreting the soot volume fraction data directly since the path length containing the soot particles is not well defined, and currently the glass tube inner diameter 33mm was used for the path length for consistency.

Conclusions

The process of formation of soot in partially premixed flames was investigated in this study. This was done in a co-annular burner with overall velocity and equivalence ratio maintained constant. The fuel content in the core stream was varied from 100 % of the total fuel to 10%, to span the regimes of fully diffusion to fully premixed flame.

It was found that the soot luminosity decreased when progressing from diffusion to premixed conditions. It was also observed that the start of the luminous region moved up gradually as the conditions moved away from diffusion flame.

From LII data, it is observed that there is a clear shift of the peak soot location inward with the increase in premixing. The LII technique proved to be ineffective in capturing the finer particles of soot even at lower laser fluences. Thus the soot luminosity was used predominantly for discussions.

For 40% case, it was observed that the rich and lean premixed flame branches appear and that marks the onset of receding soot luminosity zone from the burner lip. For cases below 40%, it was seen that the sooting region was in between the rich premixed flame and the diffusion flame. The onset of luminous zone is pushed downstream as the rich premixed flame develops into becoming a cone. The luminous zone disappears when the rich premixed flame assumes a full conical shape. The color of the luminosity also suggests that the temperature of the soot zone decreases with premixedness.

The laser extinction measurements of soot volume fraction also tend to agree with the LII measurements and the luminous zone observations in flame images.

Thus it is reasonable to claim that the soot development process in partial premixed flame regime, requires heated fuel with less air, with high temperatures. The fuel concentration gradient being low might also have a role to play in this process. However, in this study its role could not be isolated. Further studies are underway to track PAH and other critical radicals in the soot formation process, along with temperature mapping.

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