Visualization of OH Chemiluminescence and Natural Luminosity of Biodiesel and Diesel Spray Combustion

Ji Zhang and Tiegang Fang *
Department of Mechanical and Aerospace Engineering
North Carolina State University
Raleigh, NC 27695-7910 USA

Abstract

Diesel and biodiesel spray combustion in a high temperature and high pressure environment was investigated in a constant volume combustion chamber. The effects of ambient gas temperature and ambient oxygen concentration on the combustion process were studied. The ambient temperatures varied from 800 K to 1200K, while the ambient oxygen concentrations varied from 21% to 9%. The results indicate that a higher ambient temperature increases natural luminosity level and decreases the lift-off length for both fuels. At the quasi-steady stage, biodiesel shows a shorter lift-off length at low ambient temperature compared to diesel, while the lift-off lengths at higher ambient temperature for both fuels are comparable. The upstream air/fuel entrainment analysis agrees with the experimental results. Results show lower flame natural luminosity of biodiesel fuel than regular diesel. Under low ambient oxygen concentration and low ambient gas temperature, ultra-low natural luminosity was observed for both fuels. Furthermore, the simultaneous measurement of OH chemiluminescence and natural luminosity has been applied to a special case. The preliminary results have shown the validity to identify the reaction regions and can help better interpret the natural luminosity signals.

*Corresponding author, tfang2@ncsu.edu
Introduction

To meet the particulate matter (PM) emission standard for compression ignition engines, researchers have worked in the fundamental aspects of spray combustion to understand the inception, development and elimination of soot [1, 2].

It is believed that soot formation starts shortly after ignition, and continues at the mixing controlled area of the spray reacting jets [3, 4]. The distance between the lift-off length and the location of first soot formation, representing the residence pathway for the soot precursors, was found to vary with fuel oxygen content and molecular structures [3]. The oxidation of soot is coupled with the formation process, but it cannot totally eliminate the generated soot due to the short residence time and limited local source of oxidizer. As a result, soot aggregates and accumulates to PM, which finally emit out of engines.

In recent years, the technique of exhaust gas recirculation (EGR) has been introduced to reduce the NOx emission as it reduces the flame temperature dramatically [5]. However, the resulted dilution of oxygen concentrations and decrease of flame temperature can lead incomplete oxidation of soot, which contributes the increase of engine-out PM emissions. The fundamental spray combustion experiments found that as oxygen concentration ambient gas decreases from 21% to 8%, which simulated different exhaust gas recirculation (EGR) levels, the total soot volume increased initially and then gradually reduced to zero [6]. The engine test demonstrated a feasible way to use EGR to reduce NOx without penalty of PM emissions [7]. Essentially, the introduction of EGR changes the ambient temperature and oxygen concentration in the charging gas. It will be of our interest to study these two factors for both conventional diesel and biodiesel fuels.

The adoption of bio-generated fuels has been approved to effectively reduce the soot emissions by extensive studies [3, 8-11]. The existence of oxygen content in biofuel enables a more complete combustion especially in the rich diffusion flame and promotes the oxidation of soot [11]. As the oxygen content in fuel increases, the larger fractions of fuel carbon are converted to carbon monoxide (CO) in the rich flame rather than soot precursors. Moreover, unlike conventional diesel, biofuel does not contain the content of aromatics, which are considered to be critical for the initial formation of benzene leading to soot [11, 12]; thus less soot formation is expected when other conditions are maintained the same. In the oxidation of soot, the hollow internal structure of biofuel soot, probably created by the internal oxygen in fuel molecules, enables a much faster oxidation rate compared to the soot generated by diesel [12]. With the obvious reduction in soot, it should be remarked that the use of biofuel may slightly increase nitrogen oxides (NOx), which is possibly due to the increased flame temperature. However, it is feasible to achieve the simultaneous reduction of soot and NOx via low temperature combustion mode [13]. While the fuel molecular composition plays an important role in soot formation, the molecular structure effect has not been fully understood and needs further study [2].

The primary goal of this paper is to study the combustion processes under different operation conditions when using biodiesel and ULSD. With the experimental measurement, results are discussed and compared with literatures.

Experimental Apparatus

A constant volume chamber was used to simulate the diesel engine operation conditions. The chamber was made of 4340 alloy metal. There are six ports in the chamber: five of them are filled with metal plugs and one is filled with a quartz window. The inner diameter of the quartz window is 100 mm. The chamber volume is 0.95 L. Before each experiment, the chamber body was heated by eight 300W cartridge heaters to 105 °C to prevent water condensation.

In this study, three gases were charged into chamber directly in a sequence of C2H6→O2/N2→Air for the premixed combustion. The ambient density was kept constant as 15.0 kg/m³ in this study. The partial pressure of each gas was tuned before each experiment run by monitoring the pressure sensor (Omega® PXI-300) in the charging tubes. Metal flame arrestors were placed at intake and exhaust channels and were regularly replaced for safety concerns. To further prevent flame flash back and protect intake ball valve, a check valve was placed between the intake ball valve and intake tube to prevent the hot gas flashing back. After all the gases were charged into the chamber, a premixing time of 50 second was permitted before ignition.

The ignition system consisted of a spark plug and a plasma coil. The plasma coil could generate a spark energy 4 times of that regular coil does, which resulted in the spark energy as 40 mJ. A common rail fuel system was used to deliver fuel at a given pressure. The high pressure pump was controlled by a PID LabVIEW® code which monitored the pressure signal feedback from the rail. The high pressure pump was driven by an electric motor. The highest rail pressure for this common rail system was 1350 bar. The injector nozzle was Bosch® DLLA 160 P 1308, which had six symmetric orifices with included angle of 160 degree. In this study, an injection trigger pulse of 0.8 ms was employed for all experimental conditions.

Regular Ultra Low Sulfur Diesel (ULSD) and Biodiesel were used in this study. The biodiesel was manufactured by a local biofuel company with cooking oil as
the feedstock. The cetane number of the biodiesel was rated as 49.6 by the manufacturer.

Figure 1. Constant volume chamber: window observation diameter: 100 mm; volume of the chamber: 0.95 L. 1: Metal plug; 2: Spark plug; 3: Intake/Exhaust lines; 4: Chamber body; 5: Plug/Window retainer; 6: Quartz window; 7: Pressure transducer; 8: Combustion chamber; 9: Fuel injector.

Measurements and Imaging Process
The chamber pressure was measured by a Kistler® 6041A sensor. Water cooling was provided to prevent the thermal shock impact. The sensor was coupled with a Kistler® 5004 charge amplifier.

The first part of this paper measured the natural luminosity and hydroxyl radical chemiluminescence separately. In this part, a high speed camera (Phantom® 4.3) with a Nikon® 50-mm f/1.8 lens was used to capture the natural luminosity of the spray combustion. It provided the speed of 13,029 frame per second at the resolution of 128×128 with the minimum exposure time of 2 µs in this study. The digital resolution of the image was 8 bit for each pixel. By integrating the pixel value over an image, it provides the value of spatially integrated natural luminosity (SINL). Since the optical configurations for all operation conditions were same, it was feasible to compare the SINL for different conditions.

Additionally, the hydroxyl radical chemiluminescence was captured by an intensified CCD (from ANDOR Technology, model DH712-18F-03) with a UV Nikkor 105-mm f/4.5 and a band pass filter (310 nm, 10 nm FWHM from Edmund optics). The ICCD had a 512×512 pixel resolution and was gated to provide an exposure time of 300–700 µs depending on the need to elucidate the spatial lift-off length. The derived spatial resolution was 0.207 mm/pixel. The Micro-Channel Plate (MCP) gain of the intensifier could be varied from 0 to 255 to acquire the clear images without over exposure. For each condition, the images were averaged result of 5 repeated runs.

The second part of this paper measured the natural luminosity and hydroxyl chemiluminescence simultaneously in a high speed way. The incoming light from spray combustion was split by a short wave pass filter (CVI Melles Griot), which passed the UV light and reflected in 45 degree the visible and near infrared light. The natural luminosity was captured again by the Phantom high speed camera, which was configured as 15,037 frames per second. Meanwhile, the hydroxyl chemiluminescence was imaged by a Kodak 4540 high speed motion analyzer coupled with a NAC ILS-3 Intensified Lens Camera, which provided intensified images at 4500 frame per second. The exposure time was 90 µs. The resolution was 256×256, while intensifier gain was adjusted to meet the imaging requirement.

Separate Measurement Results
The SINL curves under 21% and 9% oxygen concentration conditions for diesel and biodiesel are shown in Figure 2. These two oxygen concentrations simulate no EGR and high EGR operation mode respectively. The SINL curves develop in a similar way for biodiesel to diesel. In general, biodiesel produces less soot luminosity compared to diesel at the same temperature. Biodiesel shows a later start of soot luminosity and smaller SINL increasing rate at the same temperature. This agrees with the oxygenated fuel experiments in Ref [14], which reported an increased soot inception time and longer lift-off length compared to conventional diesel fuel. Under this operation condition, the SINL decreasing rates are similar for both fuels, implying that the availability of oxygen may not be the controlling parameter to determine the late cycle burnt out process. Higher content of oxygen in molecules of biodiesel reduces the local equivalence ratio in the rich region, shifting the reaction toward the stoichiometric direction, therefore promoting the local flame temperature, and in turn reduces the soot luminosity. The local flame temperature would be a good measure to tell the effect of temperature on soot luminosity evolution. The adiabatic flame temperatures near the stoichiometric equivalence ratio for oxygenated fuel were calculated to be approximately 10–20 K higher than that of diesel fuel [15], however, the difference may be higher with the larger change of equivalence ratio across the jet flame.

The decreasing slope of biodiesel curves in Figure 2(b) is comparable to that of diesel curves, though the peak values of diesel curves are all larger than the peak value of biodiesel curves at the same temperature. It is noted that the values of decreasing slopes in Figure 1(b) are smaller than the values of the corresponding curves in Figure 2(a). It implies that the less availability of oxygen for diesel fuel could prevent soot being oxidized promptly. At low ambient temperature, the use of high level EGR reduces the soot luminosity for biodiesel, while it does not have the same positive effect for
diesel. The slow reaction under lower temperature high EGR condition for diesel prevents soot being thoroughly oxidized, which will contribute to the engine-pipe-out particle matters. The peak positions of the SINL curves for biodiesel shift toward an earlier time to the left. This shift is more apparent under the high EGR level than that under no EGR level.

Figure 2. Spatially Integrated Natural Luminosity (SINL) of diesel and biodiesel combustion. Unit of SINL is arbitrary. The start of time axis represents the start of injection trigger signal. SINL were measured and processed with the same imaging configuration and post treatment algorithm. Ambient density: 15.0 kg/m^3.

OH-chemiluminescence images for two fuels under three different temperatures and two EGR levels are shown in Figure 4 and 5 respectively. To obtain the clear images with sufficient signal levels, the ICCD gain had to be tuned to a proper value, which was labeled on the top right corner of images. Each image was an averaged result of 5 experiments. The start of the ICCD gate was carefully chosen based on the high speed images. The start time was chosen when the spray combustion had reached quasi-steady stage. The gate was tuned for best image quality. For example, in the diesel 9% O_2 800K case, the gate was tuned to be 0.55 ms, which was the longest gate among all conditions, because even the maximum ICCD gain did not provide enough signal input if a shorter gate was used; on the other hand in the diesel 21% O_2 1200K case, the gate was 0.25 ms with gain of 170, which produced a clear image. The manipulation of gate and gain of ICCD partly illustrates the strength of the OH signal input.

In Figure 4, diesel and biodiesel OH-chemiluminescence are plotted in top and bottom rows respectively for a better comparison. The jet-to-jet difference is illustrated by the top-right image, which is the diesel combustion at low ambient temperature without EGR. It is hard to directly compare the intensity of the images due to different configuration of gain and gate. However, in terms of qualitative analysis, lower temperature cases show less OH chemiluminescence, which is indicated by the dramatic increase of gain value. Lower temperature also increases the lift-off length for both fuels. The bottom-right of Figure 2 clearly shows the lift-off length and indicated the flame spatial location, which is similar to the results in Ref. [15].

In Figure 5, OH-chemiluminescence images are shown with high EGR at both high and low temperature for both fuels. Considering the left two images in Figure 3, with the same gain value, biodiesel at high ambient temperature shows a higher intensity of OH chemiluminescence signal, indicating a faster reaction may be present. Diesel and biodiesel both show very weak signal of OH chemiluminescence at low temperature, while biodiesel has a slightly stronger signal. This indicates the slow and low temperature reaction characteristic for these two cases. The low temperature and high EGR level cases present the lowest peak SINL level as well as the OH chemiluminescence for both diesel and biodiesel, showing the possibility to operate engine in a soot-free mode.

By analyzing each jet in every image, a jet-to-jet averaged lift-off length can be obtained. This averaged lift-off lengths under different conditions for both fuels are illustrated in Figure 3. Under low ambient temperature, the lift-off lengths decrease with the increase of oxygen concentration; meanwhile, biodiesel shows a smaller value than diesel under the same condition. The reason that biodiesel is easier to ignite can be attributed to the oxygen content in the fuel molecules. Considering a fuel droplet being injected out of nozzle, the local equivalence ratio is close to positive infinity. When it is heated and mixed with ambient air (oxygen), the local equivalence ratio drops quickly, and when this ratio reaches the ignition limits, the fuel ignites. The oxygen content in fuel molecule helps to reduce the local equivalence ratio in a faster way; therefore, biodiesel shows a shorter lift-off length at low ambient temperature.
condition. On the other hand, the difference between biodiesel and diesel lift-off lengths is much smaller at high ambient temperature condition. The lift-off lengths seem to reach a limit when the ambient temperature increases, implying that the effect of oxygen content may be relieved by other factors such as the required evaporating and mixing time for liquid fuels.

![Figure 3. Lift-off length for diesel and biodiesel. Ambient temperature: 800K, 1000K, 1200K. Ambient oxygen concentration: 21%, 15%, 9%. Ambient density: 15 kg/m3. Error bar stands for the standard deviation of the lift-off lengths measured for different jets.](image)

Preliminary Results of Simultaneous Measurement

The simultaneous measurement of OH chemiluminescence and natural luminosity was applied to a special case in which biodiesel was used in the ambient condition of 1100K and 21% O2. Other controlling parameters were listed in Figure 6.

To better take advantage of the camera resolution, both cameras were set up to target only one spray jet. Since the frame rates were different for two cameras, the images were selected from two measurements to be at nearly identical time points (Figure 6). In the following interpretation, only the jet at 3 o’clock is considered.

When the jet is spreading downstream (ASOI ~0.88 ms), the location of OH cloud is slightly closer to the nozzle in the upstream direction compared to the location of NL cloud. At the location where NL shows highest intensity, OH is hardly to be seen. This illustrates the major contribution of NL in the downstream regime comes from the hot soot incandescence. At the time point ASOI ~1.54 ms and ~1.98 ms, it is seen from NL images that the distance at which liquid evaporates and begins to reaction is maintained stable. These two time points are therefore considered quasi-steady state. At the quasi-steady state, the location where OH shows strong intensity shows a medium distance from nozzle. This is the regime where NL shows medium strong signal. This implies the strong high temperature reaction occurs in this region. In the region close to wall, NL shows strong signal while OH shows much weaker signal. It may imply that when the hot mixture reaches the wall, the impingement does not encourage any further reaction; instead, the less availability of oxygen in this region promotes the formation of soot.

Concluding Remarks

In this paper, the OH chemiluminescence and natural luminosity were visualized for different oxygen levels at different ambient temperatures. A case study of simultaneous measurement of OH chemiluminescence and natural luminosity has been analyzed.

- Ambient temperature plays an important role in determining the combustion process. Though higher temperature promotes the soot formation and oxidation at the same time, the overall effect is to promote the soot luminosity levels at quasi-steady stage.
- Higher EGR level reduces the peak SINL levels. For biodiesel, only at lower temperature the effect of EGR level on SINL can be observed.
- OH chemiluminescence images have shown that high EGR level greatly shifts the reaction toward the low temperature direction, featuring a much weaker OH chemiluminescence. The lowest OH signal was shown in the case of diesel combustion at high EGR level and low ambient temperature.
- At low ambient temperature, lift-off length decreases with the oxygen level increases; biodiesel shows a smaller lift-off length than diesel under the same condition. The differences become less when the ambient temperature increases.
- The combination of OH and NL images shows the high temperature reaction regions in a time and spatially resolved manner. The highest intensity of NL mainly comes from the soot incandescence, while medium intensity signal of NL shows the reaction regions.

Acknowledgements

This research was supported in part by the Faculty Research and Professional Development (FRPD) Fund from the North Carolina State University and by the Natural Science Foundation under Grant No. CBET-0854174.

References

Figure 4. OH-chemiluminescence images of diesel and biodiesel under no EGR level. Temperature: 800K, 1000K, 1200K. Ambient O2 volume concentration: 21%. White circle represents the window observation boundary. White cross represents the nozzle location. Images are the averaged results of 5 repeated tests with the same gain. Gain value for each test is labeled at right top corner. Intensifier gain ranges from 0 to 255. Time after start of injection (ASOI) when the imaging starts: diesel, 1200K: 0.7 ms; diesel, 1000K: 0.8 ms; diesel, 800K: 0.7 ms; biodiesel, 1200K: 0.8 ms; biodiesel, 1000K: 0.8 ms; biodiesel, 800K: 0.8 ms.
Figure 5. OH-chemiluminescence images of diesel and biodiesel under high EGR level. Temperature: 800K, 1000K, 1200K. Ambient O2 volume concentration: 9%. White circle represents the window observation boundary. White cross represents the nozzle location. Images are the averaged results of 5 repeated tests with the same gain. Gain value for each test is labeled at right top corner. Intensifier gain ranges from 0 to 255. Time after start of injection (ASOI) when the imaging starts: diesel, 1200K: 0.75 ms; diesel, 1000K: 0.8 ms; diesel, 800K: 0.9 ms; biodiesel, 1200K: 0.8 ms; biodiesel 1000K: 0.85 ms; biodiesel, 800K: 0.9 ms.
Figure 6. Simultaneous measurement of OH (upper row) and natural luminosity (lower row) of a single combustion case. Fuel: Biodiesel. Ambient temperature: 1100 K. Ambient oxygen: 21%. Ambient density: 15 kg/m$^3$. Injection duration: 1.6 ms. Injection pressure: 1000 bar.