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Soot and Liquid-Phase Fuel Distributions in a Newly Designed Optically Accessible D.I. Diesel Engine

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**SOOT AND LIQUID-PHASE FUEL DISTRIBUTIONS IN A
NEWLY DESIGNED OPTICALLY ACCESSIBLE D.I. DIESEL ENGINE***

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ABSTRACT

Two-dimensional (2-D) laser-sheet imaging has been used to examine the soot and liquid-phase fuel distributions in a newly designed, optically accessible, direct-injection Diesel engine of the "heavy-duty" size class. The design of this engine preserves the intake port geometry and basic dimensions of a Cummins N-series production engine. It also includes several unique features to provide considerable optical access.

Liquid-phase fuel and soot distribution studies were conducted at a medium speed (1200 rpm) using a Cummins closed-nozzle fuel injector. Mie scattering was used to obtain planar images of the liquid-phase fuel distribution. These images show that the leading edge of the liquid-phase portion of the fuel jet reaches a maximum length of 24 mm, which is about half the combustion bowl radius for this engine. Beyond this point virtually all the fuel has vaporized. Soot distribution measurements were made at a high load condition using three imaging diagnostics: natural flame luminosity, 2-D laser-induced incandescence, and 2-D elastic scattering. This investigation showed that the soot distribution in the combusting fuel jet develops through three stages. First, just after the onset of luminous combustion, soot particles are small and nearly uniformly distributed throughout the lumi-

nous region of the fuel jet. Second, after about 2 crank angle degrees a pattern develops of a higher soot concentration of larger sized particles in the head vortex region of the jet and a lower soot concentration of smaller sized particles upstream toward the injector. Third, after fuel injection ends, both the soot concentration and soot particle size increase rapidly in the upstream portion of the fuel jet. Pockets of high soot concentration and larger soot particles persist in both the upstream and head vortex regions through the remainder of the apparent heat release. At all stages soot is found to be distributed throughout the cross section of the fuel jet.

INTRODUCTION

An improved understanding of the in-cylinder processes is needed to develop new Diesel engines that can meet the stringent future emission standards for particulates and NO_x. Laser-based diagnostics can provide the temporally and spatially resolved measurements required for this improved understanding. However, the application of laser diagnostics to a Diesel engine is complicated by the need to provide sufficient optical access while maintaining a realistic combustion chamber geometry.

This article presents the design of a new optical-access Diesel engine of the "heavy-duty" size class and the results of soot and liquid-phase fuel distribution studies in this engine. This new research-engine design provides considerable optical access, a method for rapid cleaning of the windows, and a realistic combustion chamber geome-

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try. Utilizing the optical access of this engine two studies were performed. First, the liquid-phase fuel distribution was investigated using Mie scatter imaging, and second, soot distribution measurements were made throughout the combustion event using three imaging diagnostics: natural flame luminosity, planar laser-induced incandescence (LII), and planar elastic scattering.

EXPERIMENT DESCRIPTION

Optical-Access Engine

The new optical-access engine is a single-cylinder, direct-injection, 4-stroke Diesel engine based on a Cummins N-series production engine. The N-series engine is typical of heavy-duty size-class Diesel engines with a bore of 140 mm and a stroke of 152 mm. These dimensions are retained in the optical-access engine, and a production Cummins N-series cylinder head is used so that production engine intake port geometry is also preserved. Figure 1 presents a schematic of the engine, and Table 1 summarizes its specifications.

The design of this engine utilizes a classic extended piston with piston-crown window similar to that originally introduced by Bowditch in 1961 [1], however, it also incorporates several unique features. A window in the cylinder head provides a view of the squish region and the outer portion of the combustion bowl. A modular design of the piston allows the trade off between the amount of optical access and the realism of the combustion chamber geometry to be varied. When the piston-crown window is installed, the combustion bowl has a flat bottom (Fig. 1a), but combustion can be viewed throughout the bowl and simultaneously in the squish region. Alternatively, if a more complex bowl shape is desired, the piston-crown window can be replaced with a machined aluminum bowl, as shown in Fig. 2, and a significant fraction of the combustion may still be viewed through the cylinder head window. Additional windows located around the top of the cylinder wall provide the orthogonal optical access required for two-dimensional (2-D) laser imaging diagnostics. Unlike laser windows in many optical-access Diesel engines, these cylinder-wall windows permit the laser sheet to enter the cylinder along the axis of the

fuel jet as well as in a horizontal plane (see Fig 1a). Finally, but perhaps most important for Diesel combustion studies, this new optical access engine incorporates a unique separating cylinder liner to allow rapid cleaning of the windows (see Fig. 1b). A complete description of this engine may be found in Ref. 2.

Table 1. Engine and Injector Specifications

Engine Type....	Single-Cylinder, Four-Stroke, DI Diesel
Bore	140 mm (5.5 in)
Stroke	152 mm (6.0 in)
Displacement	2.34 liters (142 in ³)
Compression Ratio.....	11:1
Injector Type.....	Closed-Nozzle, Unit Injector
Number of Holes	8
Hole Diameter	0.203 mm (0.008 in)
Length/Diameter of Holes (L/D)	3.9
Angle of Fuel-Jet Axis (from horizontal)	14°

This research engine is equipped with the Cummins SELECT electronic fuel injector. This closed-nozzle unit injector uses camshaft actuation to build injection pressures. A solenoid valve in the injector body controls the amount of fuel injected and the injection timing upon command from the laboratory computer. With this injector design, changing the amount of fuel injected at a given operating condition changes only the injection duration and not the initial injection rate. For the experiments presented here, the injector was equipped with an 8-hole cup. The hole diameter was 0.203 mm (0.008 in) and the nominal angle of the fuel-jet axis was 14° downward from horizontal. The injector is instrumented with a Hall-effect needle lift sensor, and injection pressure is determined from strain gage measurements of the force in the pushtube that activates the injector.

To minimize vibration, the engine was connected to a balancing box with counter-rotating balancing weights and mounted on a spring-mounted isolation pad. The engine was motored and its speed controlled by a 75 hp dynamometer. An air compressor supplied pressurized intake air that was dehumidified and heated. The in-cylinder flow field of a similar Cummins N-series research engine has been examined under motored conditions and found to be nearly quiescent [3].

Figure 1. Schematic of the optical-access Diesel engine. Figure 1a shows the upper liner in the operating position. The in-cylinder processes can be observed through the piston crown window and/or the window in the cylinder head. Figure 1b shows the upper liner in cleaning position. The upper liner slides down allowing the interior optical surfaces to be accessed through two large openings.

Figure 2. Geometry and optical configuration of the "production" combustion chamber. The piston is shown at the TDC position.

Operating Conditions

All the data presented in this report were taken at an engine speed of 1200 rpm. Before conducting the experiments the engine was heated to 95° C by means of electrical heaters on the "cooling" water and lubricating oil circulation systems. To minimize the rate of window fouling and to avoid overheating, the engine was fired once every 20th engine cycle, at which time the data were acquired. Two fuels were used: 1) a Diesel reference fuel was used for the liquid-phase fuel distribution studies, and 2) a low-sooting fuel was used for the investigation of the soot distribution. For both fuels, special attention was given to select engine operating conditions which provide combustion characteristics typical of a production Cummins N-series engine. The two fuels and their respective operating conditions are described below, and this information is summarized in Table 2.

Table 2. Engine Operating Conditions

Engine Speed	1200 RPM
Compression Ratio	11:1
Reference Fuel.....(67.6% heptamethylnonane and 32.4% <i>n</i>-hexadecane: cetane no. = 42.5)	
Intake Air Temperature	433 K (160° C)
Intake Air Pressure (absolute)	206 kPa
Peak Injection Pressure	66 MPa
Average Equivalence Ratio.....	0.21
Low-Sooting Fuel.....(80% 2,ethoxyethyl ether and 20% heptamethylnonane)	
Intake Air Temperature	308 K (35° C)
Intake Air Pressure (absolute)	147 kPa
Peak Injection Pressure	84 MPa
Average Equivalence Ratio.....	0.43

The reference fuel used in this study was a 42.5 cetane number mixture of the Diesel reference fuels, heptamethylnonane and *n*-hexadecane. To obtain a realistic ignition delay and premixed burn fraction with the 11:1 compression ratio of this optical-access engine, the intake air was heated to 433 K (160 °C). The intake pressure was set to 206 kPa absolute to match the TDC air density of a naturally aspirated engine with the 16:1 compression ratio of an N-series production engine.

Because optical attenuation was severe with conventional Diesel fuels, a low-sooting fuel was used for the soot distribution studies, as reported in previous studies [2, 4-6]. A basic assumption in using a low-sooting fuel for soot imaging is that the combustion process is mixing-rate limited during the part of the cycle when the soot measurements are made, and that the differences in the combustion chemistry with the low-sooting fuel cause changes only in the amount of soot formed and not its spatial distribution. Because the vaporization rate can affect mixing, care was taken to insure that the low-sooting fuel constituents had similar boiling points to Diesel fuel constituents. The low-sooting fuel used was a blend of 80% 2,ethoxyethyl ether and 20% heptamethylnonane, by volume. With the closed-nozzle injector used for this study, the ignition delay was found to be shorter for the low-sooting fuel than for the reference fuel. To compensate for this, the intake air temperature was reduced to 308 K (35° C). The

intake air pressure was also reduced (to 147 kPa absolute) to match the TDC density of the reference fuel operating condition. In addition, the fueling rate was increased until the integral of the apparent heat release rate matched that of the reference fuel, since the low-sooting fuel is partially oxygenated and its energy content is lower. With these operating conditions the apparent heat release rate for the low-sooting fuel was found to be nearly identical to that of the reference fuel.

Data Acquisition and Optical Setup

Cylinder pressure, fuel injection pressure, and injector needle lift were monitored for all operating conditions. All three measurements were digitized and recorded at half crank-angle-degree increments and ensemble averaged over 20 engine cycles. Apparent heat release rates were calculated from the cylinder pressure data using the typical first law and perfect gas analysis (see for example Heywood [7]).

For the 2-D laser imaging diagnostics, LII and elastic scattering, a frequency-doubled (532 nm) Nd:YAG laser was used. The beam was formed into a sheet about 300 μm thick and 30 mm wide. Laser energies prior to entering the cylinder were about 185 mJ per pulse. For the elastic scatter images, a half-wave plate was used to rotate the polarization of the laser, making it horizontal to maximize the scattered signal collected in the vertical direction. This is necessary to obtain a strong elastic scatter signal from the small soot particles, but less significant for the larger liquid fuel droplets. The laser sheet was directed through a window in the retainer ring which was in line with one of the fuel jets at an angle of 14° upward from horizontal, so that it bisected the fuel jet as shown in Fig. 1a.

The laser-induced optical signals were collected through the window in the cylinder head by a gated, intensified, CCD video camera. Appropriate filters were placed in front of the camera to isolate either the LII or the elastically scattered laser light as discussed in the next subsection. In addition to the filters, flame luminosity was further suppressed by a short exposure time synchronized with the 8 ns laser pulse. The minimum gate width

on the camera intensifier was about 25 ns, which was used for all laser sheet images. Natural flame luminosity images were also acquired with the intensified CCD camera by removing all the filters and increasing the intensifier gate width to 1 μ s. The camera had a resolution of 512 by 480 pixels, and was connected to an 8-bit frame grabber in an AT-type personal computer.

Synchronization between the engine, laser, camera, and intensifier gate was controlled by a second AT-type computer and a digital delay generator. This synchronization system could be adjusted to obtain images at any desired crank angle within the half degree resolution of the shaft encoder. Although each image is time resolved to nanosecond time scales, only one image could be acquired in a given cycle due to speed limitations of the laser and video recording system. Images were acquired in sets of 12, from 12 separate cycles. Each image presented has been subjectively selected as being representative of its respective set.

Optical Diagnostics

For each of the three diagnostics used, a brief discussion of the principles and image interpretation is given below.

Natural Flame Luminosity - Although several factors can affect their interpretation, natural flame luminosity images can provide information about the soot distribution in a combusting Diesel fuel jet [5,8,9]. In highly sooting flames like those of Diesel engines, the natural luminosity is dominated by gray body emission from combustion-heated soot, with the intensity of the luminosity from any point in the plume being a function of the local soot volume fraction and the temperature. Natural luminosity images give a picture of the luminous soot emission integrated along the line of sight to a depth dependent on the optical density of the plume. With the low-sooting fuel, the plume has a low optical density, and emission from soot at all elevations through the plume contributes to the natural luminosity image [2, 4]. Therefore, the flame luminosity images presented in Fig. 7 provide a picture which is representative of the total soot along the line of sight through the plume.

LII - LII images are generated by collecting the thermal radiation from soot particles that have been heated by a sheet of pulsed laser light. When laser power densities are on the order of 10^7 W/cm² or greater, the temperature of the soot is increased to a temperature near its vaporization temperature (about 4500 K) on time scales similar to the rise time of the laser pulse [4,10]. By exploiting the temperature difference between this laser-heated soot and the non-laser-heated soot (whose temperature is about 2200 K [9]), the natural flame luminosity can be removed from the LII images through appropriate spectral filtering and camera gating. Assuming that the soot behaves as a gray body, the thermal emission of the laser-heated soot will be much greater than that of the non-laser-heated soot, especially at shorter wavelengths. For this study, it was found that a 450 nm short-wave-pass (SWP) cutoff provided the best rejection of background luminosity while still allowing a sufficiently strong LII signal. Using a combination of 450 nm SWP filters and the minimum camera-intensifier gate width of 25 ns, the contribution of background luminosity to the LII images was found to be negligible. Elastic scattering of laser light from liquid droplets and in-cylinder surfaces was completely rejected by adding a 532 nm laser-line mirror (which acts as a band-reject filter) to the 450 nm SWP filters. A complete discussion of the technique may be found in Ref. 4.

Interpretation of LII images is straightforward under ideal conditions. Areas of high and low image intensity represent regions of high and low soot concentrations, respectively. Melton [10] predicts that in the limit of high laser power, if laser and signal attenuation are negligible, the signal strength from laser-heated soot should be directly proportional to the local soot volume fraction (particle diameter to the third power). Although proper calibrations to verify this would be difficult to achieve in an engine, it seems reasonable to assume that, if attenuation effects are small, the relative intensities in an LII image provide information about the relative soot volume fractions (concentrations). Measurements of the LII intensity at various elevations through the combusting plume [6] and comparisons of the LII intensity

with simultaneous flame luminosity images [5] in our former research engine have demonstrated that, with the low-sooting fuel, attenuation was sufficiently low for relative concentrations to be determined from the LII images. Arguments similar to those discussed in Ref. 5 may be made for the LII and luminosity images presented in this article.

Elastic (Mie) Scattering - As a laser-sheet traverses the combustng fuel jet in a Diesel engine, some of the light will be elastically scattered by the liquid fuel droplets and/or soot particles in its path. Collecting this scattered light allows both soot and liquid fuel distributions to be imaged, however, interpreting the images can be difficult if soot and liquid fuel exist in the same area. Flame luminosity and LII can be easily suppressed using a short exposure time and a narrow-band-pass filter centered about the laser line. In this study, a 25 ns camera-intensifier gate width and a 532 nm narrow-band-pass filter, 10 nm FWHM, were used. Although flame luminosity and LII were adequately rejected, laser light scattered from in-cylinder surfaces can cause noise problems for elastic scatter imaging, as discussed in Refs. 4 and 5.

Elastic scatter signal intensity is strongly dependent on the particle size. For small particle sizes typical of soot (Rayleigh limit), the elastic scatter signal is proportional to the particle diameter to the sixth power [11]. If a range of soot particle sizes is present, this relationship, coupled with dynamic range limitations of the camera, can bias the images to regions of larger soot particles. The relationship between elastic scattering intensities and particle size is more complex for liquid fuel droplets which are typically much larger than the Rayleigh limit. As a result, the elastic (Mie) scatter images of the liquid fuel provide only a qualitative picture of where liquid fuel droplets are, or are not, present.

LIQUID-PHASE FUEL MEASUREMENTS

The liquid-phase fuel distribution was visualized using Mie scatter imaging and the Diesel reference fuel. With the selected intake air conditions (433 K and 206 kPa), the motored TDC temperature and pressure of our 11:1 compression ratio

research engine are estimated to be 1050 K and 5.0 MPa, respectively. These conditions are representative of typical Diesel engine TDC conditions. As mentioned above, the Cummins CELECT injector gives the same initial fuel injection rate for all fuel loads at a given operating condition. Since this study is concerned only with the initial penetration and vaporization of the liquid-phase fuel, a low total-fuel-load operating condition was used (average equivalence ratio of 0.21).

Results

Figure 3 shows a temporal sequence of liquid-phase fuel images obtained through the piston-crown window. In each image the white spot near the left edge marks the location of the injector tip, and the white curve near the right edge marks the edge of the combustion bowl (see Fig. 1a). The horizontal distance from the injector to the edge of the bowl is 49 mm, and the number in the lower right of each image gives the crank angle degree after top dead center (ATDC). The fuel spray is angled downward 14° from horizontal, and the laser sheet enters the field of view from the right along the axis of the fuel jet in the 3 o'clock position. Although previous investigations [2] have shown that all eight fuel jets are very uniform, the Mie scatter signal intensity varies greatly from jet to jet due to nonuniform illumination. Because the laser sheet is attenuated as it travels down the 3 o'clock fuel jet, the signal is weak except for the region near the tip. In addition, because the injector is not oriented exactly with respect to the laser sheet, the jet in the 4 o'clock position is illuminated from the side so it appears very bright, and the jet in the 2 o'clock position is shadowed by the 3 o'clock jet so it appears relatively dim. However, the tip of the 3-o'clock jet is consistently well illuminated so it can be used to follow the liquid-phase fuel penetration.

Following the image sequence in Fig. 3 we see that at -10.5° no fuel injection is evident. In the next image, one degree later, fuel is just beginning to emerge from the holes. Then for the next 3 degrees the extent of the liquid fuel increases rapidly reaching a length of about half the bowl radius (about 24 mm) by -6.5° . Beyond -6.5° , the liquid

Figure 3. Temporal sequence of Mie scatter images of the liquid-phase fuel distribution. The white dot to the left of each image shows the location of the injector and the white curve to the right shows the edge of the combustion bowl. The laser sheet travels from right to left up the axis of the fuel jet in the 3 o'clock position. The engine speed is 1200 rpm.

Figure 4. Liquid fuel penetration, injector needle lift and injection pressure. Figure 4a shows the maximum liquid fuel penetration with crank angle as measured from Mie scatter images. The curve is a cubic spline fit to the data. Figure 4b shows the injector needle lift and injection pressure ensemble averaged over 20 cycles. The engine speed is 1200 rpm.

length remains fairly constant at about 24 mm. For this operating condition, combustion begins about -5° , and by the time of the last image in Fig. 3 (-3.5°) soot from the combustion is beginning to obscure the liquid fuel. Thus, the visible liquid length in the -3.5° image may not be accurate and images are not presented at later crank angles.

A plot of the maximum liquid-fuel penetration with crank angle is shown in Fig. 4a. This plot shows data from all of the 12 images which were acquired at each crank angle. The solid line is a cubic spline fit to the data. Although there is some spread in the data due to cycle-to-cycle variation, the trend is consistent. Initially the liquid fuel penetrates linearly with increasing crank angle until reaching a maximum length of 24 mm at -6.5° . The liquid length then remains nearly con-

stant even though fuel injection continues until -1° , as shown by the injector needle lift record in Fig. 4b. Therefore, virtually all the liquid fuel must be vaporized by the time it reaches a distance of 24 mm from the injector. These results are in agreement with our previous study [6] in which the liquid fuel was found to reach a distance about 35 mm from the injector at a colder (about 703 K) TDC air temperature, while the vapor-phase fuel penetrated much farther. They are also in agreement with a study by Kamimoto et al. [12] which showed a limited liquid penetration.

The timing of the start of injection relative to the indicated needle lift may also be determined from the plots in Figs. 4a and 4b. From the image data in Fig. 4a, we see that fuel injection begins just prior to -9.5° . The needle lift curve, which was digitized at half degree increments, shows no measurable lift at -9.5° but a small lift at -9° . Since the uncertainty between the timing of the two measurements is less than 0.25° , these data show that actual fuel injection begins at or slightly before the very first indicated needle lift for this injector.

SOOT DISTRIBUTION MEASUREMENTS

The soot distribution within the combusting Diesel fuel jet was measured using planar imaging of LII and elastic scattering. These measurements were made with the low-sooting fuel, in order to reduce optical attenuation to an acceptable level. Operating conditions were selected to give the same apparent-heat-release-rate record as the Diesel reference fuel for a high fuel-load case (average equivalence ratio of 0.43), as summarized in Table 2. A plot of the cylinder pressure, needle lift, and apparent heat release rate for the low-sooting fuel at the selected operating condition is presented in Fig. 5.

The soot distribution images were obtained through the cylinder-head window using the flat-bottomed combustion chamber modified with a cut in the bowl rim. As shown in the schematic presented in Fig. 6, the piston-top ring was cut out, in line with the imaged fuel jet, to allow the laser sheet to enter the combustion chamber near TDC. If the bowl rim were intact, the leading edge of the

Figure 5. Apparent heat release rate, cylinder pressure and needle lift for the low-sooting fuel at a high fuel load (average equivalence ratio of 0.43). The engine speed is 1200 rpm and the data are ensemble-averaged over 20 cycles.

Figure 6. Geometry and optical configuration of the flat-bottomed combustion chamber with cut out in the rim for laser access. Figure 6a shows a side view of the combustion chamber, while Figure 6b shows the top view of the piston. The piston is shown at the TDC position.

plume would contact it 1° to 2° BTDC and be deflected [2]. Although the lack of a bowl rim means that after 1° or 2° BTDC the soot distribution is not representative of a real engine, much can be learned about the behavior of combusting fuel jets under Diesel conditions by examining the later images.

Results

Temporal sequences of natural flame luminosity, planar LII, and planar elastic (Mie) scatter images are presented in Figs. 7a and 7b. In each part of Fig. 7, the images in the top row are flame luminosity, those in the middle row are LII, and those in the bottom row are elastic (Mie) scattering. These images are not simultaneous, but have been selected from sets of twelve images from twelve different engine cycles. Figure 7a contains images from -2.5° ATDC to 7.5° ATDC, while Fig. 7b contains images from 9.5° ATDC to 17.5° ATDC, as indicated at the top of the figures. The black outline around each image shows the field of view through the cylinder-head window. As shown in Fig. 6, the 48.5 mm diameter cylinder-head window overlaps the cylinder wall making the width of the field of view 43.5 mm. In these images, the combusting fuel jet propagates from left to right, with the injector being located 26.5 mm to the left of the field of view as shown in Fig. 1. Since the maximum liquid fuel penetration is 24 mm (Figs. 3 and 4) and the injector is 26.5 mm to the left of the field of view, liquid fuel does not contribute to the elastic scatter soot images in Fig. 7. The laser sheet propagates from right to left along the axis of the fuel jet at an angle of 14° upward from horizontal. Assuming that the fuel jet is globally axisymmetric, this laser-sheet location allows the soot distribution throughout the fuel jet to be obtained in a single image at any given crank angle.

The natural flame luminosity images in the top row give a general picture of the luminous (sooting) combustion. Because the plume has a low optical density when the low-sooting fuel is used, these images provide a picture of the natural flame luminosity integrated along the line of sight through the plume. All the luminosity images, except the one at -2.5° , were taken with the same

camera aperture so image intensities at the different crank angles may be compared. Because the flame luminosity was much weaker at -2.5° , a wider camera aperture was required, and the intensity of the -2.5° image cannot be directly compared to those at later crank angles.

The planar LII and elastic scatter images in Fig. 7 provide detailed information about the soot distribution in the midplane of the fuel jet. As discussed in the subsection on Optical Diagnostics, the LII signal intensity is proportional to the particle diameter to the third power, while the elastic scatter signal intensity (in the Rayleigh limit) is proportional to the particle diameter to the sixth power. Therefore, LII image intensity provides a measure of the relative soot concentration, while the elastic scatter image intensity provides combined information about both the soot particle size distribution and concentration. By comparing the elastic scatter images with the LII images, the relative particle size distribution may be deduced. Because laser light that is elastically scattered off in-cylinder surfaces contributes a background signal to the elastic scatter soot images, all the elastic scatter images presented, except the one at -0.5° , have been corrected by subtracting a background image obtained with no fuel injection. All LII images were taken with the same camera aperture so intensities may be compared, as were all the elastic scatter images.

The first LII image (-2.5°) shows that shortly after the onset of luminous combustion, soot is present throughout the cross section of the luminous region of the fuel jet. Initially, the soot concentration is almost uniform throughout the combusting fuel jet, but by -0.5° a pattern develops of a higher soot concentration in the head vortex region and a lower concentration upstream. This soot concentration pattern persists through the remainder of the sequence in Fig. 7a as the overall soot concentration increases and the combusting fuel jet penetrates to the cylinder wall.

The first elastic scatter image presented is at -0.5° *. This image shows a weak elastic scatter

* An elastic scatter image at -2.5° is not presented because the signal was too weak to adequately distinguish it from the background scatter.

Figure 7a. Temporal sequence of natural flame luminosity, laser-induced incandescence (LII), and elastic (Mie) scatter images from 2.5° BTDC to 7.5° ATDC. The crank angle ATDC is given at the top of each set. The engine speed is 1200 rpm and the average equivalence ratio is 0.43.

Figure 7b. Temporal sequence of natural flame luminosity, laser-induced incandescence (LII), and elastic (Mie) scatter images from 9.5° to 17.5° ATDC. The crank angle ATDC is given at the top of each set. The engine speed is 1200 rpm and the average equivalence ratio is 0.43.

signal throughout the jet (barely distinguishable from the background scatter) and a slightly stronger signal around the leading edge of the head vortex. A comparison with the corresponding LII image shows that this intensity pattern could result from variation in the soot concentration, although the soot particles could also be slightly larger at the leading edge. In any case, the variation in elastic-scatter signal intensity is small, and the signal intensity is much lower than at subsequent crank angles. This suggests that initially the soot particles are small throughout the jet with a nearly uniform size distribution.

At the next crank angle presented, 1.5° , the elastic scatter image has a high intensity in the head vortex region, particularly around the periphery of the leading edge. The corresponding LII image shows that the soot concentration has increased only slightly from -0.5° , and that the soot concentration pattern is nearly the same. As a result, the change in the elastic scatter image from -0.5° to 1.5° must be due to an increase in particle size in the head vortex region of the jet.* Thus, the combination of images at 1.5° shows that: 1) soot is present throughout the cross section of the luminous portion of the combusting fuel jet, 2) in the head vortex region, the soot concentration is higher and the soot particles are larger, and 3) upstream toward the injector, the soot concentration is lower and the soot particles are smaller. This same soot concentration and size-distribution pattern then continues through the remainder of the fuel injection period (through the 7.5° images).

Immediately following the end of injection, the images in Fig. 7 show a distinct change in the soot distribution pattern. For this operating condition injection ends at about 9° ATDC as shown in Fig. 5. At 9.5° , the LII image shows a higher soot concentration developing in the upstream portion of the jet. Similarly, at 9.5° , the elastic-scatter image intensity is also higher in the upstream region, indicating that there are now larger particles in the upstream region. By 11.5° the new

soot distribution pattern is well developed. There is a high soot concentration and larger soot particles in the upstream region of the jet as well as in the remains of the head vortex. This pattern persists with the soot concentration slowly decreasing for the remainder of the image sequence. By the time of the final image in Fig. 7b the heat release is nearly complete, as shown in Fig. 5.

Discussion

We believe that this change in the soot distribution with the end of injection occurs as a result of the injector needle throttling the flow through the injector holes as it closes. This causes the last fuel to be injected at a lower velocity than the previous fuel, so it cannot catch up with the leading edge of the jet. As a result, this last fuel does not mix well with the in-cylinder air, but remains along the axis of fuel jet. The result is a high degree of soot formation with the particles growing to a larger size. In support of this hypothesis, it should be noted that the changes in the soot distribution with the end of injection, found in the current study, were not noticed by the authors in a previous study in a similar research engine fitted with a Cummins PT open-nozzle injector [5]. The open-nozzle injector is designed so the last bit of fuel is forced out under high pressure, in contrast to a typical closed-nozzle injector, such as the one used in the current study.

Finally, Fig. 7b shows that the pockets of high soot concentration and large soot particles along the jet axis persist well into the expansion stroke, and are still present near the end of the heat release. Although we have not made measurements of the tail pipe emissions from this engine, it is possible that these pockets of soot formed near the end of injection do not oxidize well and contribute preferentially to particulate emissions.

SUMMARY AND CONCLUSIONS

Two-dimensional (2-D) laser-sheet imaging has been used to examine the soot and liquid-phase fuel distributions in a newly designed, optically accessible, direct-injection Diesel engine of the heavy-duty size class. The design of this engine preserves the intake port geometry and basic

* For the elastic scatter images from 1.5° to 7.5° , the weak elastic scatter signal in the upstream region was lost when the background scatter was subtracted.

dimensions of a Cummins N-series production engine. It also includes several unique features to provide considerable optical access. An extended piston with piston-crown window provides a full view of the combustion bowl, while a window in the cylinder head allows simultaneous observation of the squish region. Windows at the top of the cylinder wall provide orthogonal-optical access with the unique capability of allowing the laser sheet to enter the cylinder along the axis of the fuel jet. Perhaps most important for the application of optical diagnostics to Diesel combustion, the design also incorporates a unique separating cylinder liner to allow rapid cleaning of the windows. For all measurements, the engine was operated at a medium speed of 1200 rpm, and a Cummins electronically controlled closed-nozzle fuel injector was used.

Liquid-phase fuel distribution measurements were made using Mie scatter imaging. This study showed the following:

1. Fuel injection begins at the very first indication of injector needle lift as measured by a Hall-effect sensor.
2. Initially, liquid fuel penetrates linearly with increasing crank angle until reaching maximum length of about 24 mm 3° after the start of injection.
3. The liquid fuel penetration length then remains roughly constant for at least 3 more crank angle degrees, at which time soot obscured the measurements.

Planar laser-induced incandescence (LII), planar elastic (Mie) scattering, and natural flame luminosity imaging were used to investigate the soot distribution within the combusting fuel jet for a high load condition (average equivalence ratio of 0.43). This study showed the following:

1. Soot occurs throughout the cross section of the luminous portion of the fuel jet from near the end of the premixed burn until near the end of the heat release.
2. Initially, the soot concentration is nearly uniform and the soot particles are small throughout the plume.
3. About 2-4 crank angle degrees later (about 1.5° ATDC), a pattern develops of a higher soot

concentration and larger-sized particles in the head vortex region, and a lower soot concentration and smaller-sized particles upstream toward the injector.

4. With the end of injection, both the soot concentration and the particle size increase in the upstream region.
5. Pockets of high soot concentration and larger particles persist along the jet axis for several degrees after the end of injection.

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