Development of a quantitative measurement of a diesel spray core using synchrotron x-rays

Christopher F. Powell[◆], Yong Yue[★], Sreenath Gupta[★], Armon McPherson[◆], Ramesh Poola[★], and Jin Wang[◆]
[◆]*User Program Division, Argonne National Laboratory, Argonne, IL 60439 USA*
[★]*Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439 USA*

Introduction

Detailed analysis of the fuel spray process is an important step in the goal of increasing combustion efficiency and reducing emission of pollutants, in particular from diesel engines. Increased injection pressures and smaller orifice diameters for small-bore engines have brought even greater impetus to the understanding of fuel spray behavior. These interests have spurred considerable activity in the development of optical techniques for measurements of diesel fuel injection systems [1-8]. Despite significant advances in laser diagnostics over the last 20 years, the region close to the nozzle has remained impenetrable to experiments designed to acquire quantitative information due to the large number and high density of droplets in the region. While other researchers are looking into the possibility of using ultra-high power lasers to penetrate this region, we report here the development of a new non-intrusive and quantitative technique to characterize the dense part of the fuel spray using x-ray absorption techniques.

X-rays have an intrinsically low cross section when interacting with matter, and multiple scattering is typically a negligible component of x-ray measurements. Therefore, x-rays are highly penetrative in materials composed of extremely dense droplets made of low-Z materials. This makes x-rays a useful tool for spray studies designed to overcome the difficulties encountered by conventional research utilizing visible light. There have been x-ray radiographic studies on liquid core structure of coaxial jets made of high-Z materials on relatively large length scales using x-ray tube sources [9]. In the experiment, polychromatic x-ray beams were used as the radiographic light source, and a quantitative analysis of the absorption was extremely difficult, if not impossible. Therefore, a quantitative study of sprays must utilize a monochromatic x-ray beam. We report here the measurement using x-ray absorption of monochromatic synchrotron-generated radiation, allowing quantitative determination of the fuel density distribution in this optically impenetrable region with a time resolution better than one microsecond. The current quantitative measurements constitute the most detailed near-nozzle study of a fuel spray to date.

Methods and Materials

The fuel spray was generated using a high-pressure injector typical to a passenger car. The diesel fuel used was doped with a cerium-containing compound in order to increase the x-ray absorption of the fuel. Injection was performed into a spray chamber filled with flowing inert gas at atmospheric pressure and room temperature. SF_6, a very heavy gas, was used to create a relatively dense ambient environment in the injection chamber.

The experiments were performed at the 1-BM beamline of the Advanced Photon Source (APS). A 5.989 keV x-ray beam was focussed then collimated by a pair of X-Y slits to a size of 500 µm (horizontal) × 50 µm (vertical). The transient x-ray attenuation signal due to the fuel spray was measured by an avalanche photodiode (APD). The APD response was proportional to the beam intensity over the intensity range used in our experiment and was recorded every 2 ns by a digitizing oscilloscope. Since the APD is a point detector, the injection chamber was translated vertically and horizontally with respect to the x-ray beam, allowing the beam to probe various positions within the spray plume. The x-ray absorption technique using a monochromatic beam is distinguished from earlier measurements near the nozzle by the quantitative nature of the measurement. With proper calibration, the x-ray absorption technique can determine the absolute mass and the mass distribution. The absorption of a known quantity of fuel was measured in quartz capillary tubes. This provided a calibration of the absorption, allowing the mass of fuel in the path of the beam to be determined from the time-resolved attenuation data. In addition, anomalous absorption was measured above and below the Ce L_{III} edge at 5.723 keV [10] to confirm this calibration.

Results

A plot of the time-dependent x-ray transmission 1 mm and 6 mm from the nozzle is shown in Fig. 1.

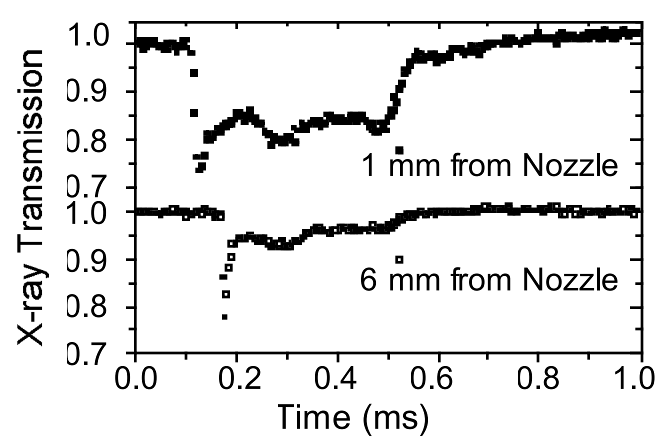

Figure 1: Time evolution of the x-ray transmission on the spray axis 1 mm and 6 mm from the nozzle.

For the data measured 1 mm from the nozzle, the fuel has not yet intersected the x-ray beam for time t < 0.1 ms, and the transmission is near 1. At t = 0.11 ms, the fuel intersects the x-ray beam resulting a sharp decrease in the transmission. This leading edge of the fuel spray appears very abruptly, indicating a very distinct boundary between ambient gas and fuel spray. This leading edge also represents the highest density region of the spray. After the leading edge, the transmission increases, and oscillates over a range of a few percent. At t = 0.5 ms, the trailing edge appears as the fuel exits the x-ray beam and the transmission returns near to the baseline value. Note that the transmission is greater than unity after the injection because the vaporization of the fuel displaces the strongly attenuating SF_6 gas. At 6 mm from the nozzle on the spray axis, the leading edge of the spray arrives at the measuring point at a later time (0.19 ms).

This delay can be used to calculate the speed of the leading edge, which was determined to be very close to the speed of sound in SF_6 (~150 m/s). While the absorption of the leading edge remains similar to the value measured at 1 mm, the absorption of the body of the spray decreased significantly, indicating a low fuel volume fraction at this location.

Based on the transmission values and the mass calibration, the amount of fuel in the path of the beam can be determined in a time-resolved manner. The total mass in the beam as a function of the radial measuring position can be represented very well by a Gaussian distribution (data not shown). In planes that intercept the spray perpendicular to the spray axis, the fuel distribution is assumed to be circularly symmetric, which is supported by the symmetry in absorption values measured above and below the spray axis, and by the fact that a circular nozzle was used. It is then reasonable to model the radial distribution of the fuel density as a Gaussian along the radial axis.

The normalized density (volume fraction) distribution is plotted in Fig. 2 for the leading edge of the spray (upper panel) and the main body of the spray (lower panel) at distances of 1 and 6 mm from the nozzle. The most striking feature of the plots in Fig. 2 is that the density of the fuel spray was significantly less than that of the bulk liquid fuel, even as close as 1 mm from the nozzle. The only part of the spray with a density close to the bulk liquid density was the thin leading edge, which had a maximum density about 75% of that of the liquid 1 mm from the nozzle. The main body of the spray, the region that has been termed the “liquid core,” is actually composed of a liquid/gas mixture. When the main body of the spray had traveled 6 mm from the nozzle, the density of the spray core had dropped to less than 10% of the liquid density.

Discussion

Using x-rays, it was possible to probe a much denser region of the spray than any study reported to date. As close as 1 mm (~5.5 nozzle diameters) from the nozzle, we found that the central region of the spray does not exist as a pure liquid jet. Other studies have come to similar conclusions at somewhat larger distances from the nozzle. Gülder *et al.* found no “liquid core” in the range from 8 mm to 47 mm from the nozzle with measurements utilizing skimmers, laser diffraction, and laser sheet illumination [11]. The current work extends even closer to the nozzle, and utilizes a nonintrusive and quantitative technique. These features are essential to the development of accurate theoretical models of fuel sprays.

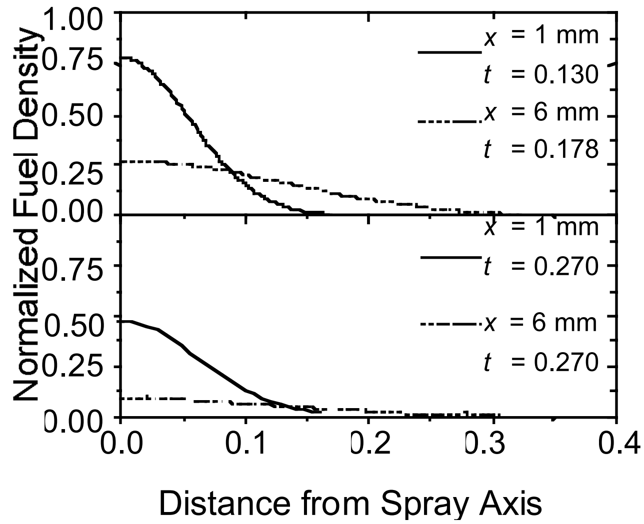

Figure 2: Normalized radial distribution of the fuel density measured 1 and 6 mm from the nozzle at different instants in time (leading edge or main body of the spray intercepting the beam, respectively). A normalized density equal to unity implies the density of bulk liquid fuel (injection pressure: 500 bar, duration: 300 μs).

The complete time-dependent behavior of the fuel density is currently under analysis. With the completion of this work, a very detailed picture of the near-nozzle region will be unveiled.

In summary, we presented the first attempt to use monochromatic x-ray radiography to study diesel fuel sprays. The measurement is quantitative and highly time resolved. The preliminary results indicate that the core region near the nozzle is composed of a liquid/gas mixture with a density less than 50% of that of the bulk liquid as close as 1 mm from the nozzle (500 bar, 300 s, SF_6 gas). Our initial results have demonstrated that this technique is well suited for elucidating the spray structure near the nozzle orifice. We believe that the technique can become a powerful and complementary method to other techniques including those utilizing visible light and lasers.

Acknowledgments

Argonne National Laboratory under the Coordination Council for Science and Technology program sponsored this work (U.S. Department of Energy, under contract W-31-109-Eng-38). The authors wish to acknowledge Robert Bosch, Corp., for providing the diesel fuel injection system used in this work. The authors are thankful to J. Schaller, J. Fettes, K. Berta, P. Bohl, and M. Schlebusch of Robert Bosch Corporation for providing technical support. We thank P.V. Satyam for his initiative efforts. The authors are thankful to P. Fournier-Bidoz of Rhodia Terres Rares for providing the cerium additive. The assistance from R. Cuenca and R. Sekar is very much appreciated. We also thank S. Smith, W. McHargue, and P. Lee of ANL for their support during the experiments. This work and use of the Advanced Photon Source was supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under Contract No. W-31-109-Eng-38.

References

[1] H. Hiroyasu, *Fifth International Conference on Liquid Atomization and Spray Systems, Gaithersburg*, 17–31 (July 1991).
[2] R.R. Maly, *SAE* **910727** (1991).
[3] C. Gang, *Progress in Energy Combustion and Science* **22**, 163–188 (1997).
[4] R.J. Adrian, *Ann. Rev. of Fluid Mech.* **23**, 261–301 (1991).
[5] I. Shimizu, *SAE* **820355** (1982).
[6] C.N. Yeh *et al*., *SAE* **932652** (1993).
[7] M.A. Coil, *SAE* **950458** (1995).
[8] W-Q Long *et al*., *JSME International* **39**(3), 554-561 (1996).
[9] R.D. Woodward *et al*., *Recent Advances in Spray Combustion: Spray Atomization and Drop Burning Phenomena, American Institute of Aeronautics and Astronautics*, *Inc.*, 185–210 (1995).
[10] Henke, B. L. et al, *Atomic Data and Nucl. Data Tables*, **54**, 181–342 (1993).
[11] Ö.L. Gülder *et al*., *SAE* **920577**, (1992).