Measurement of Direct Injection Gasoline Fuel Sprays Using Synchrotron X-rays

Y. Yue, C. F. Powell, R. Poola, J. Wang
Argonne National Laboratory, Argonne, IL, U.S.A.

Abstract

A quantitative and time-resolved technique has been developed to probe the dense spray structure of direct-injection gasoline sprays in the near-nozzle region. This technique uses the line-of-sight absorption of monochromatic x-rays from a synchrotron source to measure the fuel mass with a time resolution better than 1 μs. The small scattering cross section of fuel at the x-ray regime allows direct measurements of the spray structure that would be difficult with most visible-light optical techniques. Appropriate models have been developed to determine the fuel density as a function of time.

Introduction

Gasoline direct injection (GDI) is being considered as a promising technology for future light-duty vehicles. In GDI engines, fuel is directly injected into the cylinder. As in direct injection (DI) diesel engines, the spray characteristics and mixing process play an important role in the combustion process. Understanding gasoline spray characteristics is important in designing nozzle geometry and GDI engines; it is also vital to realistic computational modeling. To ensure high combustion efficiency and low emissions, well-atomized sprays and proper spray penetration are always required over the entire GDI engine operating range to achieve better engine performance. Despite significant advances in laser diagnostics over the last 20 years, the region close to the nozzle has remained impenetrable, and so quantitative data about this region are lacking.

X-rays have an intrinsically low cross section when interacting with matter, and multiple scattering is a negligible component of x-ray measurements. Therefore, x-rays are highly penetrative in low-atomic-number materials consisting of extremely dense droplets. The x-ray absorption method is a new nonintrusive method that can be used to quantitatively measure the spray density.

Experiment Aspects

A brilliant monochromatic x-ray beam tuned to 6 keV at the SRI-CAT 1-BM beamline was used in this investigation. For a monochromatic x-ray beam with precise mass absorption calibration, the x-ray absorption data can determine absolute mass in the beam. The x-ray beam was focused and collimated to a size of 140 μm (horizontal) × 50 μm (vertical). The transient x-ray attenuation signal due to the fuel spray was measured by using a fast-response avalanche photodiode detector (APD) with a temporal resolution of approximately 5 ns. Since the APD is a point detector, mapping the absorption (attenuation) of the fuel spray involved translating the injection chamber vertically and horizontally with respect to the x-ray beam. The total number of position samples is about 1600. A GDI injection system with an outwardly opening injector was employed. Spray was injected into a spray chamber filled with an inert gas (nitrogen) at atmospheric pressure and temperature. The fuel used in this study was a blend of calibration type gasoline fuel and a cerium-containing additive. The blend had a cerium concentration of about 4.2% by weight. The collimated beam then passed into the injection chamber for probing the fuel sprays.

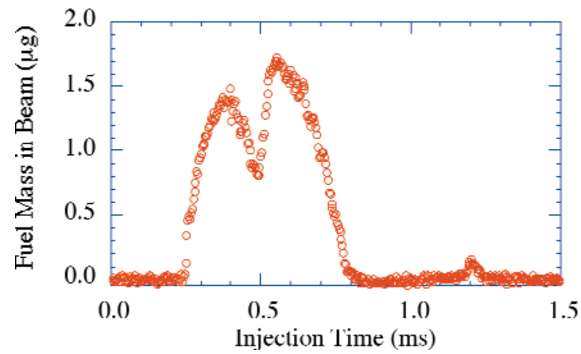

FIG. 1. Time-evolution of integrated fuel mass in the beam.

Results and Discussion

The instantaneous mass in the beam can be precisely evaluated on the basis of measured x-ray transmission and the mass calibration. The resulting time evolution of fuel mass in the beam measured at 2 mm from the nozzle and 2.22 mm from the hollow-cone spray axis are shown in Fig. 1. The plot depicts the typical features of our absorption measurements. In this particular measurement case, at the very beginning (0.23 ms), the fuel has not yet reached the measuring point. At a later time (0.24 ms), the fuel intersects the x-ray beam. A large fluctuation of the fuel mass can clearly be seen in the plot during injection, which shows that the injection process is unsteady. At an even later time (0.8 ms), the trailing edge appears as the fuel exits the x-ray beam, and the fuel mass returns to the baseline value. In addition, after the main spray exited the measuring point, a small but clearly observable peak is found at 1.18 ms, showing that there was a second injection attributable to the bounce of injector nozzle.

Given the high temporal resolution of x-ray measurements, the projected mass distributions in Fig. 2 are reconstructed on the basis of point-by-point measurements of 1600 positions. The time value shown in the figure relates to the instance when measurements began. The mass distribution inside the spray plume changes with injection time. With the profile of the total mass in the beam, it is possible to extract the model-dependent volume fraction of the fuel at any instance of time and in space assuming a cylindrical symmetry. An attempt was made to de-convolute the volume fraction of fuel as spatial and temporal functions, and the result is illustrated in Fig. 3, which shows that, the best fit to the measured x-ray transmission is in the plane that intersects the fuel spray cone perpendicular to the spray axis (2 mm from the nozzle exit). In such a near-nozzle region, the thickness of the spray plume is less than 50 μm, while the fuel density is much smaller than liquid gasoline density (0.3 in volume fraction).

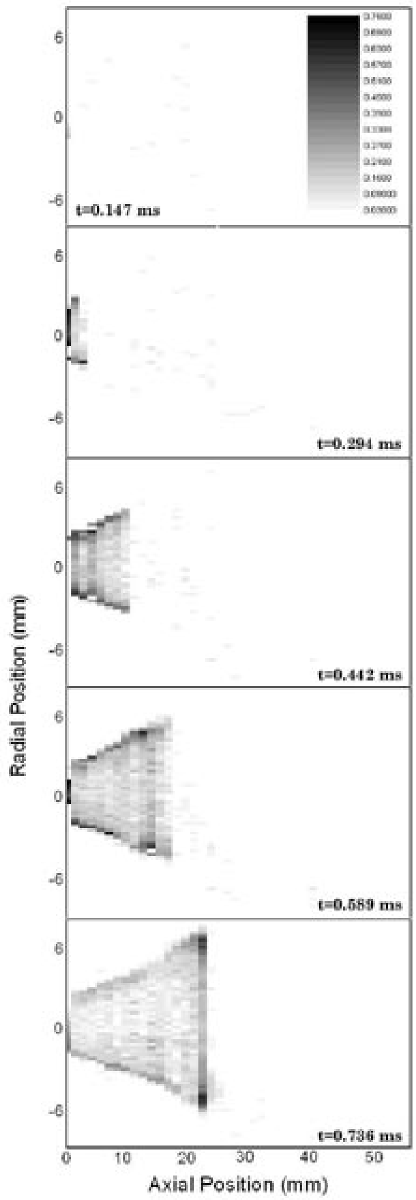

FIG. 2. Reconstructed snapshots of two-dimensional projected mass distributions at the indicated time instances.

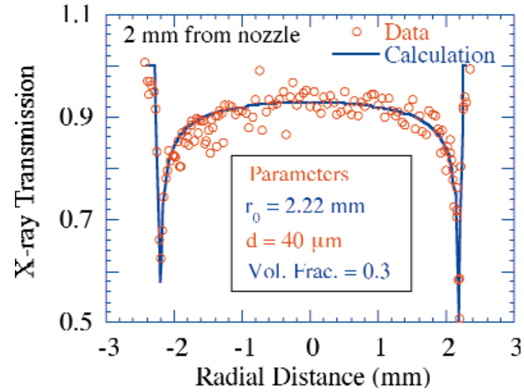

FIG. 3. Fit (line) to the experimental transmission data (circles) across the hollow-cone spray. The parameters obtained from the fit are indicated.

Summary

In this report, the first attempts to investigate GDI sprays by means of monochromatic x-ray radiography are presented. The measurement is quantitative and highly time resolved. It has been clearly demonstrated that the x-ray technique is a powerful complementary tool to fully characterize the fuel spray. Based on the initial fitting results, the thickness of the spray hollow cone is much smaller than expected. Therefore, in addition to the high temporal resolution, a high spatial resolution, such as that applied in the current study, is much needed in the region near the spray nozzle and at the edge of the spray.

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