X-ray Imaging of Shock Waves Generated by High-Pressure Fuel Sprays

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Synchrotron x-radiography and a fast x-ray detector were used to record the time evolution of the transient fuel sprays from a high-pressure injector. A succession of 5.1-microsecond radiographs captured the propagation of the spray-induced shock waves in a gaseous medium and revealed the complex nature of the spray hydrodynamics. The monochromatic x-radiographs also allow quantitative analysis of the shock waves that has been difficult if not impossible with optical imaging. Under injection conditions similar to those found in operating engines, the fuel jets can exceed supersonic speeds and result in gaseous shock waves.

High-pressure, high-speed sprays are an essential technology for many applications, including fuel injection systems, thermal and plasma spray coating, and liquid-jet machining (1–4). Liquid sprays are often difficult to record optically because of intense multiple light scattering from the surrounding liquid droplets. In the case of fuel injection, an understanding of the structure and dynamics of the fuel sprays is critical to optimizing the injection process to increase fuel efficiency and reduce pollutants. Despite substantial advances in laser diagnostics over the past 20 years (5–10), the region close to the nozzle still has not yielded desired quantitative information. As a result, high-pressure fuel sprays have never been recognized as supersonic under typical fuel injection conditions (11, 12). In this report, we use monochromatic x-radiography to probe the high-speed fuel sprays and show the generation of shock waves.

We studied a high-pressure common-rail diesel injection system typical of that in a passenger car with a specially fabricated single-orifice nozzle. The orifice was 178 μm in diameter, and the injection pressure could be set between 50 and 135 MPa. Fuel was injected into an x-ray–accessible spray chamber (13) filled with the inert gas sulfur hexafluoride (SF₆) at 1 atm pressure and room temperature (typically 30°C). This heavy gas allows simulation of the dense gas environment of a diesel chamber without resorting to high-pressure x-ray windows (14). The fuel was a blend of No. 2 diesel and an x-ray contrast–enhancing, cerium-containing compound, resulting in a total cerium concentration of 4 weight % (15).

We performed the time-resolved radiography of shock waves in a gaseous medium and revealed the complex nature of the spray hydrodynamics. The monochromatic x-radiographs also allow quantitative analysis of the shock waves that has been difficult if not impossible with optical imaging. Under injection conditions similar to those found in operating engines, the fuel jets can exceed supersonic speeds and result in gaseous shock waves.

For single-wavelength x-rays, the analysis of the propagation of the attenuating material (the fuel) and the leading edge of the fuel spray, as indicated by the abrupt increase in fuel mass from 0 to nearly 5 μg at t = 0.17 ms for data taken 1 mm from the injector nozzle (Fig. 1A). The sharpness of the interface facilitated the calculation of the apparent speed of the leading edge (Fig. 1B). A highly concentrated fuel region immediately followed the leading edge represented by an extremely sharp peak, which was caused by accumulation of droplets as they impacted on the ambient gas at the leading edge (19). Although the injection pressure inside the nozzle remained stable (within 5% of 50 MPa) during the injection (20),
pressure set at 80 MPa (front effect of a reflecting wall to the shock intensifier to a duration of about 0.1 s.

To visualize the density change in the shock front in the gas medium, we collimated flashed white light beam by an aperture and a collimating lens before illuminating the fuel sprays. The images were collected at the Schlieren plane. The exposure time was controlled by a gated image intensifier to a duration of about 0.1 μs. The bright circle in the images indicates the size of the observation window of the test chamber, measured at 25 mm in diameter. The imaging magnification in (B) was set slightly higher than that in (A) to emphasize the region where the reflection of the shock front occurred. The portion of the spray visualized here is the optically dense, low-mass cloud of droplets surrounding the thin, main fuel jet that can only be imaged by x-rays.

**Fig. 2.** Optical Schlieren images of the shock waves generated by fuel sprays in SF$_6$ gas collected with the injection pressure set at 80 MPa (A) and the effect of a reflecting wall to the shock front (B). The spray propagates from left to right along the axis of the injector in the imaging field. To visualize the density change in the shock front in the gas medium, we collimated flashed white light beam by an aperture and a collimating lens before illuminating the fuel sprays. The images were collected at the Schlieren plane. The exposure time was controlled by a gated image intensifier to a duration of about 0.1 μs. The bright circle in the images indicates the size of the observation window of the test chamber, measured at 25 mm in diameter. The imaging magnification in (B) was set slightly higher than that in (A) to emphasize the region where the reflection of the shock front occurred. The portion of the spray visualized here is the optically dense, low-mass cloud of droplets surrounding the thin, main fuel jet that can only be imaged by x-rays.

**Fig. 3.** Time-resolved radiographic images of fuel sprays and the shock waves generated by the sprays for time instances of 38, 77, 115, 154, and 192 μs after the start of the injection (selected from the total of 168 frames taken). The imaged area shown in the largest panel is 61.7 mm (H) by 17.5 mm (V) with data corrected for the divergence of the x-ray beam. The x-ray beam size in the experiment was 13.5 mm (H) by 2.5 mm (V), the imaged area was built up by shifting the position of the injector relative to the beam and the PAD and repeating the injection cycle. Boundaries between these areas can be seen upon close inspection. The exposure time per frame was set to 5.13 μs (twice the CHESS synchrotron period) with subsequent images taken after an additional 2.56-μs delay. Each position shown is the average of images from 20 fuel injection cycles. The detector was not positioned over all possible areas of the image, so specific images show missing areas. To optimize the conditions for the direct visualization of the shock waves, we chose the injection pressure to be 135 MPa. The contrast of the spray segment included within the two markers shown in Fig. 1A lies between the speeds of the leading and trailing edges but is much closer to that for the trailing edge (Fig. 1B), suggesting that the internal part of the spray travels much faster than the sonic speed in SF$_6$. Although these point-by-point measurements strongly indicated that the fuel spray should generate shock waves, such a method lacked spatial coverage and became impractical to directly image the shock waves.

To confirm the supersonic nature of the sprays, we visualized the shock waves in the same spray system by optical Schlieren imaging of visible light (11, 24, 25) when the injection pressure reached 80 MPa, as shown in Fig. 2A. A reflecting wall was also introduced in the testing chamber. The shock front was reflected off this wall and impinged back onto the spray (Fig. 2B). The influence of the reflected shock front on the appearance of the spray was not determined with statistical significance. As expected, the optical images yielded only the cone angle of the shock wave.

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The calculated speed of the spray wave can be seen much more clearly in the "movie" of successive frames (26).
Mach cone, as shown in Fig. 4. In the plane perpendicular to the jet axis, the shocked region is a cone with an excess density in the SF$_6$ of about 0.6 $\mu$g/mm$^2$ measured at 10.4 mm from the spray tip. Behind the high-density region, the interior of the cone has a small but observable reduction in the gas density from the ambient (Fig. 4B), which implies that decompression has occurred away from the Mach cone. Although there is no simple hydrodynamic interpretation to explain the observation, this behavior is different from the compression shock waves generated by a rigid object (27).

The manner in which the shock waves affect the atomization of the fuel and the combustion processes is currently unknown. With more injection systems adopting preinjection technology (a short pilot injection before main injection), the engine cylinders are likely to be filled with fuel vapor-air mixture under high temperature before the main spray arrives. It has been recognized that the mixture would have a sonic speed lower than that of either fuel vapor (<130 m/s at room temperature) or air, so the generation of shock waves by the main fuel injection should not be surprising, even at elevated engine operating temperature. In this regard, the presence of the dense fill gas used in our study (SF$_6$) mimics this injection condition. This study has paved the way to directly study the complete range of fluid dynamics inside and close to high-pressure liquid sprays. The time-resolved x-radiographic method should also prove useful in characterizing highly transient phenomena in optically dense materials, such as dense plasma and complex fluid-gas interactions.

References and Notes
14. SF$_6$ a heavy gas with molecular weight of 146, was used to simulate the relatively dense ambient gas environment in a diesel engine during the adiabatic compression part of the engine cycle when the diesel fuel is normally injected. The sonic speed in SF$_6$ at room temperature (30°C) is 136 m/s [22], considerably less than the 330 m/s speed of sound in air at the same temperature. Fuel sprays with much higher speeds can be generated at the higher injection pressures used in diesel engines.
15. The cerium additive (DPX90, Rhodia Terres Rares) was included to increase the x-ray absorption of the fuel jet and accounted for about 50% of the total absorption at the selected x-ray energy.
18. Radiography with polychromatic x-ray beams was reported previously to study liquid jets (28). However, lack of quantitativeness seriously limited its capability of imaging and characterizing high-pressure fuel sprays. For monochromatic x-rays transmitting through a nonuniformly distributed material, the analysis of the transmission of the attenuating material is given by $I_0 = \exp(-\mu \times M)$, where $I_0$ and $I$ are the transmitted and incident x-ray intensities, respectively, $\mu$ is the mass absorption coefficient, which can be measured and calibrated accurately for the absorbing medium (fuel) at the single wavelength, and $M$ is the mass of fuel in the beam. Thus, the time evolution of the measured x-ray transmission can be simply transformed into integrated, line-of-sight fuel mass data at each point in the radiograph.
19. Because the spray is composed of an aerosol of streams and droplets, the liquid at the leading edge of the spray can move at rates quite different than those of the average body of the spray. Without the resistance or impact to the ambient gas, the spray body can move much faster than the leading edge and with speeds close to that for the trailing edge. This large speed variation can also cause accumulation of the fuel near the tip. Instantly after the nozzle opening, the high fuel concentration in the spray tip is certainly caused by the transient nature of the fuel pressure at the nozzle.
20. The injection pressure was measured both inside the nozzle and in the common rail with the same injection system and with a similar nozzle (miniscus type).
21. A shock generated by the impact of the fuel spray on the ambient gas travels within the spray body as a compressed gaseous pocket resulting in a low-fuel density region.
23. The correlation function is defined by $g(x) = \int |M(x,t)| \times \delta (x - t \sigma \Delta t, \rho = \rho') dt$. Therefore, the speed of such a fraction of the spray at the location $x$ can be estimated by $v(x) = \Delta x / \Delta t$. 
26. X-radiographic images of shock wave propagation are available in the form of animation on Science Online at www.sciencemag.org/cgi/content/full/295/5558/1261/DC1.
29. The 5-µs time resolution was a combination of the image integration time and jitter associated with synchrotron radiation. The electron timing jitter was less than 300 ns.
30. We thank R. Poola for his initiation and participation of the research, R. Cuenca and A. McPherson for their technical support, and M.-C. Lai and O. Vasiliev for discussions. Beamline support at CHESS and the APS is gratefully acknowledged. The work, use of the APS, and the PAD development are supported by the U.S. Department of Energy under contract W-31-109-ENG-38, the Freedom CAR Program, and grants DE-FG-0297ER14805 and DE-FG-0297ER62443. CHESS is supported by the U.S. NSF and the NIH under award DMR-9731424. 16 November 2001; accepted 11 January 2002.