Research Highlight

Microsecond Radiography of Fuel Injection Sprays

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The combination of very high x-ray flux and newly developed all semiconductor Pixel Array Detectors (PADs) has been used at CHESS and the APS to record, for the first time, microsecond time-resolved radiographic “movies” of the complex dynamics of fuel injection sprays.

Real fuel-injected engines operate far from theoretically optimal limits. Given the prevalence of gasoline and diesel engines, improvements of even a few percent in efficiency or pollutant reduction would have enormous beneficial consequences. The performance of a fuel-injected engine is a complex problem in multi-dimensional optimization of variables such as fuel injector nozzle geometry, injection rate of the fuel, cylinder pressure, ignition timing, etc. The goal is adjustment of the time-course of these variables to result in a desired delivery of mechanical work and combustion products. The time-honored way of optimizing a fuel injection cycle is to make a change and observe the engine performance. However, it is practically impossible to fully search the multi-dimensional “variable space”. A direct and fundamental understanding of the injection process is required.

The time-distribution of the fuel aerosols is key. For example, in gasoline direct injection (DI) engines, it is desirable to evenly disperse the fuel spray over the entire cylinder so as to result in a uniformly complete “burn”. Unexpected high-density clumps of fuel spray may result in parts of the burn being oxygen starved and higher pollution. Although fuel injectors are a fact of modern life, much is unknown about the dynamics of their sprays. The injection of fuel liquid into a gas-filled cylinder results within microseconds in a fog of liquid fuel droplets that scatters visible light so strongly near the injector nozzle that the sprays cannot be readily probed by conventional optical means. In consequence, the behavior of fuel sprays in the near nozzle region has been inferred indirectly from, for example, the distribution of liquid mechanically impacting a downstream screen. By combining screens and moving shutters it is possible to gain limited information about the dynamics of the spray. However, the full spray dynamics, i.e., the detailed spatial distribution of fuel mass as a function of time, had been difficult to obtain.

X-ray absorption is a directly mass-sensitive probe. Radiography with x-rays above an absorption edge of a dopant atom added to the fuel (e.g., cerium) can be used to greatly increase the contrast in the radiographic images, thereby allowing observation of even fine details in fuel vapor streams. Point-by-point measurements by scanning the spray showed that, for a given set of injection variables, the spatial-temporal fuel distribution is very reproducible [1]; however, these methods are impractical to map out the full 4-dimensional evolution of the sprays over an extended spatial volume. Large area imaging detectors capable of operating on microsecond time-scales are needed since an injection event lasts only 1 to 2 milliseconds.

PADs fulfill this need. A PAD, such as developed at Cornell University [3,4,5], consists of a sandwich of two silicon chips (Figure 1). The first chip consists of a 2-dimensional array of reversed-biased, fully depleted diodes that serve to stop the x-rays and produce a local electrical current proportional to the stopped x-ray energy. This current is conducted through metal connecting bumps, pixel by pixel, to a second integrated circuit chip. The second chip is a corresponding 2-dimensional array of cells of signal processing and storage electronics. Because the detection process occurs in parallel in every pixel, a PAD is capable of extraordinary time resolution.

A schematic of the electronics in each pixel is shown in Figure 2. By synchronizing the opening and closing of the CMOS switches in the pixel in concert with the

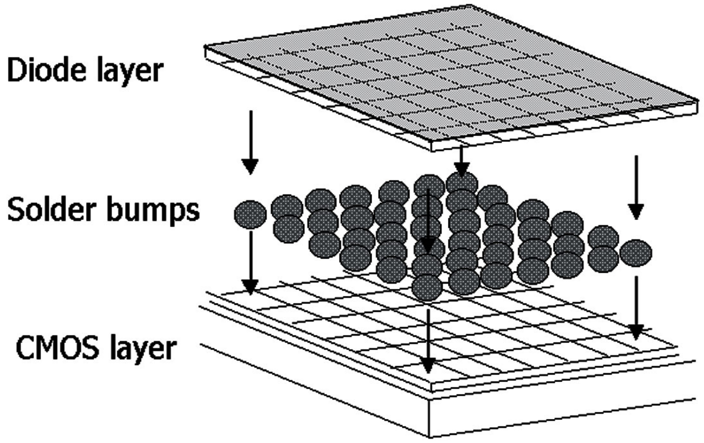

Fig. 1 Schematic of detector assembly. The PAD is comprised of two silicon wafers electrically connected using an array of solder bumps, one solder bump for each pixel. The top layer is a high resistivity wafer into which an array of x-ray detection diodes is fabricated. Charge generated by the conversion of x-rays in this layer is passed through the solder bumps into the CMOS electronics layer with integration and storage electronics built into each pixel.

phenomenon to be observed, eight frames of data may be recorded at rates adjustable from microseconds to seconds as voltages on the storage capacitors. After the eight frames of data have been stored, the exposure sequence is halted and the capacitor voltages are read out of the chip and digitized.

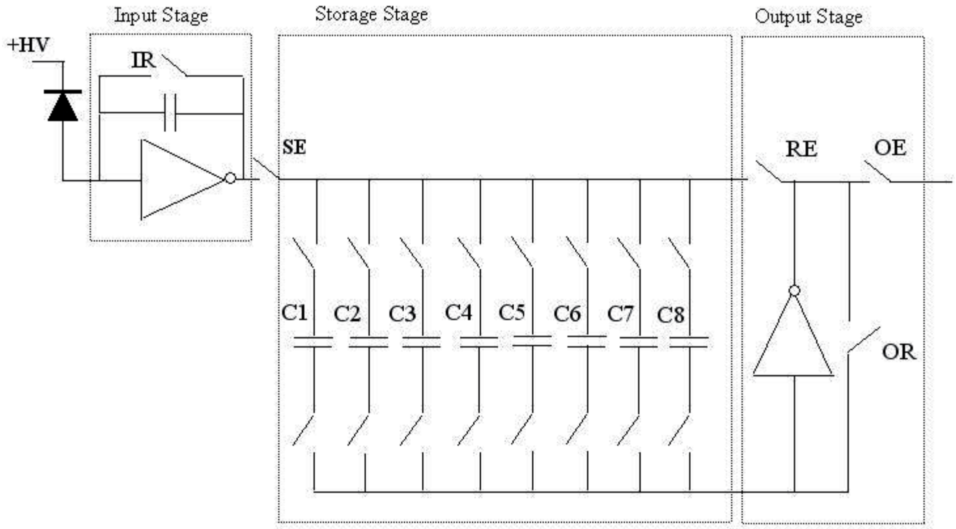

Fig. 2 Pixel circuitry schematic. Shown is the electronics integrated within the footprint of each pixel. Charge produced by x-rays in the detection diode layer is integrated onto the capacitor in the input stage. One of eight frame storage capacitors (C1 – C8) is selected using CMOS switches to store the integrated voltage level for each frame. Rapid imaging of up to eight frames is accomplished through the proper sequencing of these capacitors in concert with integration reset (IR). Frame readout is accomplished by connecting the storage capacitors in sequence with the output amplifier. SE, store enable; RE, read enable; OE, output enable; OR, output reset; IR, input reset.

Data has been collected at CHESS at both D1 and A2. The basic experimental setup involves production of a wide-area (e.g., 13.5 mm by 2.5 mm) x-ray beam from a multilayer monochromator. The injection chamber is fitted with Kapton, x-ray transparent windows to allow the beam to pass through. It sits on a stepper-motor positioning stage placed between the incident beam-defining slits and the PAD. Both diesel fuel [2] and hollow-cone gasoline DI (in preparation for publication) sprays have been observed. In the interests of simplicity and safety, neither experiment involved ignition; rather, the sprays were injected into an inert SF_6 or N_2 carrier gas. Because the spray covers a larger area than the x-ray beam footprint and because it is desirable to record more than eight time steps, the full time-resolved radiographic sequence is recorded with repeated fuel injection cycles, stepping the fuel injection inbetween in both space and time. Periodic recording of frames at given positions and times proved that the detailed features were reproducible from one injection cycle to the next. Both the injection sequence and the PAD detector were slaved to the storage ring bunch structure to ensure a normalized incident photon flux even with exposure time comparable to the storage ring periods.

Diesel fuel injectors spray a bolus stream of fuel into the chamber. No. 2 diesel fuel was mixed with a cerium-containing organo-metallic liquid to 4% cerium weight concentration and radiographed above the cerium L-edge with 6 keV x-rays. The spray stream velocity profile is complex, with part of the stream accelerating and other parts slowing down. Surprisingly, the leading edge of the spray can reach supersonic velocities, as shown in Figure 3). We believe this is the first time that a gaseous shock wave has been radiographed. The sequence of still images hardly does justice to the beautiful false-color "movie" of the spray event, which may be downloaded from the Science web-site (http://www.sciencemag.org/cgi/content/full/295/5558/1261/DC1).

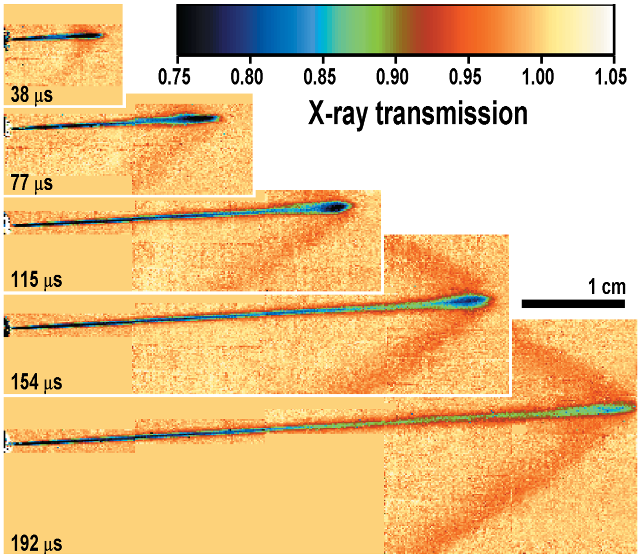

Fig. 3 This figure is from the MacPhee 2002 Science paper [2]. Time-resolved radiographic images of fuel sprays and the shock waves generated by the sprays for time instances of 38, 77, 115, 154 and 192 µs after the start of the injection (selected from the total of 168 frames taken). The imaged area 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. Because 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 detector 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, the injection pressure was chosen to be 135 MPa. The contrast of the shock wave was low, corresponding to only an average of ca. 15% increase in gas density near the shock front. Therefore, the false-color levels of the images have been set to accentuate small differences in the x-ray intensity arising from the slightly increased x-ray absorption in the compressed SF_6 gas.

Gasoline hollow-cone DI sprays are yet more complex and full of surprising structures, including traveling pressure waves, streaks originating from imperfections in the nozzle, and inhomogeneous distribution of fuel in the cone "sheet" (Figure 4). Many of these features were previously unknown to occur in the sprays. By repeating the experiment at different rotation angles of the injection cylinder relative to the beam direction it was possible to reconstruct the full 4-dimensional structure of the spray. The results (being prepared for publication) show that the cone of fuel is far from axially symmetric.

We plan to continue to study the dynamics of fuel sprays. These experiments demonstrate the power of PADs to elucidate complex time-resolved structure. They immediately suggest many other experiments involving the dynamics of complex mixed phase systems, such as ink jets, spray coatings, slurry and flocculent suspensions, and flows of powders.

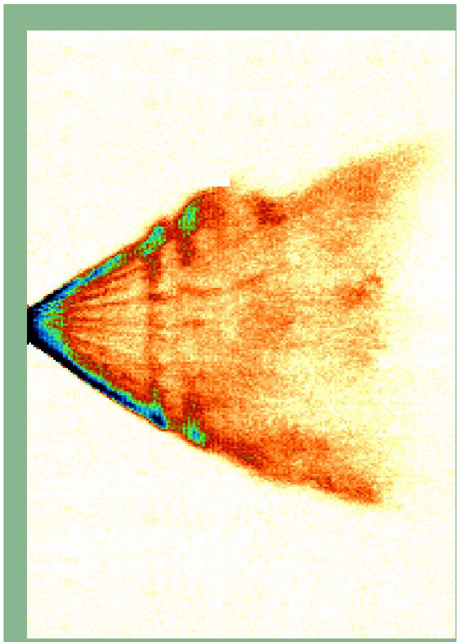

Fig. 4 A false-color x-radiograph of an approximately 5 microsecond slice of the injection cycle of a hollow-cone gasoline fuel injection 492 microseconds after the start of the injection. The false-color is adjusted so that black represents x-ray absorption greater than 15%. The composite image area is about 25 mm x 37 mm.

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