Ballistic Imaging of Sprays at Diesel Relevant Conditions

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Abstract

Diesel engines are an important aspect of our transportation infrastructure, whose performance is greatly affected by the characteristics of the spray from their injectors. Characterization of the injector's sprays is therefore key to clean-running efficient diesel motors. In this study, a ~15 ps pulsed Leopard D-10 laser is used along with an optical Kerr Cell to realize ballistic images of high-delivery-pressure (>100 MPa) dodecane sprays injected via a single 160 micron hole injector into a quiescent air environment at elevated temperature and pressure. Using CS_2 as the Kerr switching media and by optimizing the overlap of the gate and imaging beams, an effective high speed shuttering effect is obtained. This effort resulted in the first usage of a ballistic imaging technique to successfully capture the spray behavior of dodecane injected into an air environment with temperatures to 600ºC and pressures to 20 atm, typical of pre-combustion conditions of diesel engines. Control of the imaging beam arrival time after the start of injection allowed for the capture of images from separate injections that detail the spray's development over time. The resulting images demonstrate significant differences in spray behavior over a range of chamber temperatures and pressures. Specifically, at low pressure and temperature, some smooth wave structure is apparent, but at high chamber pressure, sprays show significant signs of violent mass shedding from the spray periphery.

Introduction

Diesel engines are used worldwide and are of enormous importance to transportation. In the diesel cycle, fuel is introduced into the engine cylinder at near-top-dead-center where it subsequently ignites and a fraction of the energy released by combustion of the fuel is converted to shaft power. The diesel engine is unique in that the combustible charge is heterogeneous, and as such, mixture preparation is accomplished via fuel injection immediately before and during combustion. Fuel injection heavily influences, subsequent mixing, ignition, and efficient combustion during the diesel cycle. Thus, fuel spray characteristics spare critical to diesel engine emissions and fuel efficiency. Therefore, measurements and modeling of the diesel spray are particularly complex; the flow is transient and two phase, the physics of the spray breakup is not well understood, and the high number density of droplets (and of soot in some cases) impedes classical optical measurements.

Traditionally, experimental measurements have focused on measurements of drop size and volume fraction in the dilute regions of the spray. Extensions of these measurements have been made to probe into the more optically thick regions of the spray [1], and more recently on the very near nozzle (or so-called breakup) region of the spray [2,3,4]. One of these efforts uses a technique known as "ballistic-imaging." This technique relies on the transmission of coherent light through the spray and uses an ultrafast "shutter' to separate ballistic photons that represent the variation in optical transmission as a function of position in the spray from scattered photons which typically do not carry image information. The technique relies on an optical Kerr effect and as implemented in this study relies on a 15 ps pulsed laser and CS_2 as the Kerr shuttering media. This paper reports on ballistic imaging capture of the spray behavior of high-delivery-pressure (>100 MPa) dodecane sprays injected via a single 160 micron hole injector into quiescent air at temperatures and pressures of up to 600ºC and 20 atm.. The resulting images reveal significant differences in the structure of the near-nozzle region of the spray, which appear to be strongly dependent on chamber temperatures and pressures.

Experimental Methods

An experimental schematic is shown in Fig. 1. The 532nm output from a Coherent Leopard D-10 laser operating at 10 Hz repetition rate with 12±1 mJ per pulse was used for ballistic imaging. The pulse length of the laser was measured at 15±2ps FWHM using autocorrelation, which is unique since ballistic imaging is traditional achieved via the use of sub-picosecond lasers[5]. The 6mm diameter laser beam was split into an OKE (optical Kerr effect) gate beam and an imaging beam with a 90/10 cube beam splitter; 90% of the pulse energy output from the laser was to produce the OKE gate beam. The OKE gate beam traveled across the table to a delay prism mounted on a translation stage and was then directed through a CS_2 cell. The prism and translation stage provide several 10's of picoseconds of time delay of the OKE gate beam relative to the imaging beam. A pair of linear polarizers, P1 and P2, was used to control the pulse energy on the imaging leg. To limit damage to focusing optics, the imaging beam was typically limited to < 30 μJ. P2 was aligned to pass vertically polarized light to ensure linear polarization and P1 was rotated to reduce the pulse energy on the imaging leg. The ½ waveplate (WP) was oriented to rotate the imaging beam polarization 45º. The linear polarization of the imaging beam was improved a second time with P3 oriented to pass light at 45º to vertical. The imaging beam was then directed through the spray with a turning mirror. The optical imaging train was optimized for the ballistic imaging experiment using a Zemax model. The OKE gate was formed by a pair of crossed polarizers, P4 and P5, and the OKE gate cell. P4 was oriented to pass the non-scattered image beam, while the output linear polarizer (P5) of the OKE gate was set to be crossed with P4. The OKE gate cell was composed of a pair of laser optical windows separated by 1.7mm. The intervening space was filled with spectroscopic quality CS_2. The assembly was sealed with O-rings in a 50mm diameter optical tube. The CCD is a Photometrics Cascade 650 imaging array (653x492 pixels, 7.4 µm square).

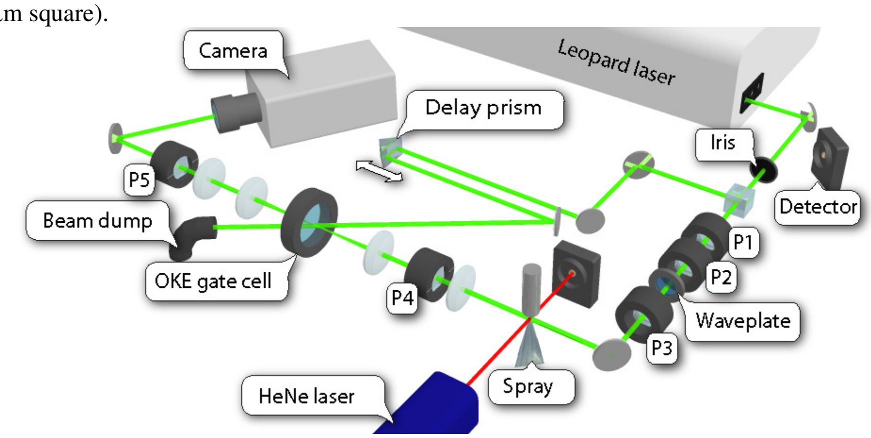

Figure 1. Experimental schematic of ballistic imaging optical train. The HeNe laser and separate detectors measure the arrival of the imaging pulse and the spray injection timing. P1-P5 are polarizers. Beams are shown cw for clarity.

The spray was generated by a Sturman® diesel fuel injector operating on dodecane. The spray was driven by a pulsed hydraulic amplifier similar to the hydraulic system described in [6]. The spray duration was tracked using a HeNe laser beam aligned to cross directly below the tip of the injector. The HeNe beam was directed to a photodiode and monitored on an oscilloscope. Spray duration, as determined by attenuation of the HeNe beam, was typically 3.0 to 3.5 ms. The imaging beam was monitored via a separate photodiode on the same oscilloscope. The arrival time of the imaging pulse relative to the initiation of the spray was determined from the oscilloscope traces.

The CCD and fuel injector were timed relative to the laser using an electronic trigger output pulse from the laser power supply. CCD exposure time was 1.0 µs and initiated with a TTL timing pulse controlled with an external delay generator, while fuel injector timing was controlled via a second delay generator. Relative timing between the laser pulse and the single shot spray event is critical to successful experiments and, in fact, what is required is control of the placement in "spray time" of the laser pulse with respect to the start of the spray. Since the laser operates on a fixed 10 Hz clock, a photodiode is used to sense the laser pulse that is one pulse before the one used for the experiment. All timing is based on this pulse with delay generators and custom electronics used to control the start of the injection sequence and the shutter open time for the CCD camera

Via the delay prism, the OKE gate beam's arrival could be set relative to the arrival of the imaging pulse as shown schematically in Fig. 2. In Fig. 2 the imaging pulse is shown arriving after the OKE gate is turned "on" by the OKE gate pulse. The time of simultaneous arrival occurs when the prism location (OKE gate pulse delay) maximizes OKE gate transmission in the absence of a spray. Timing of the OKE gate pulse, relative to simultaneous arrival, was determined by converting the linear translation, as read from micrometers on the translation stage, to time. With increasing delay between the gate and imaging pulses, OKE gate transmission decreases significantly relative to the peak transmission. This is corrected via adjustment of P1 to increase energy on the imaging leg such that the measured beam power was maintained at ~30µJ.

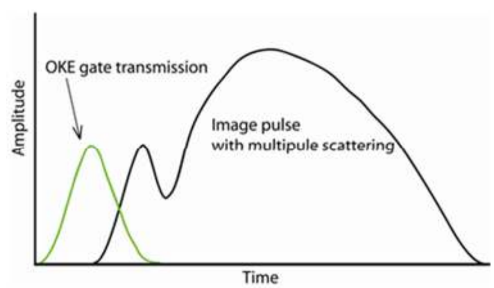

Figure 2. Time dependence of ballistic, snake, and diffuse photons relative to OKE gate transmission. The cartoon shows the image pulse arriving at the OKE cell after the OKE gate pulse.

Results and Discussion

Ballistic images of a high injection-pressure dodecane spray were captured in the CSM high-pressure facility[Fig.3]. This facility is composed of a custom-manufactured combustion vessel capable of operation at 50 atm and 1000 K, which is equipped with optical ports to facilitate imaging at diesel relevant conditions. More details and specifications are found in [7].

Dodecane was injected at 1450 atm injection pressure into quiescent air at ambient temperature (25°C) and elevated temperature (600°C) and over a range of chamber pressures from 0.9 atm to 20 atm. Spray images collected at the same injection timing but at different background temperatures and pressures are compared in Figure 4. Images have been processed to subtract the background signal. The gray-scale in the image represents, at each location, the natural log of the ratio of the attenuated beam to the un-attenuated energy in the beam. Non-uniformity in image backgrounds is due in part to variations in laser intensity and fluctuations in gas density at elevated temperature. This work has also shown the width of the spray to have transient fluctuations and a strong dependence on background gas conditions.

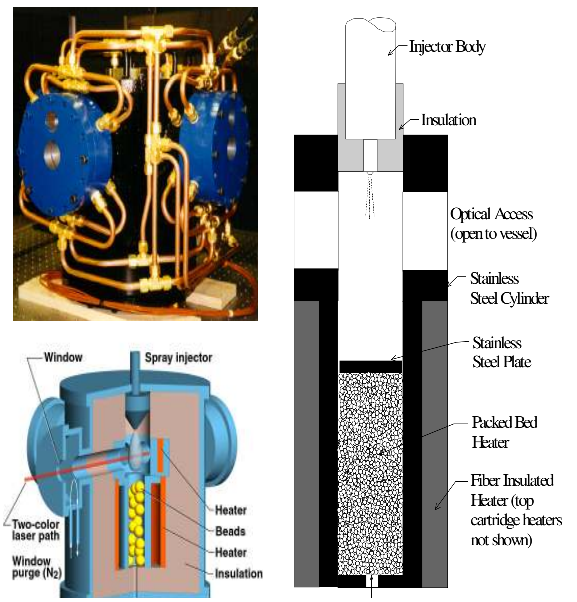

Figure 3. The High Pressure Diesel Engine Simulator. Actual hardware (top left); Cutaway view (bottom left); Interior heated core (right).

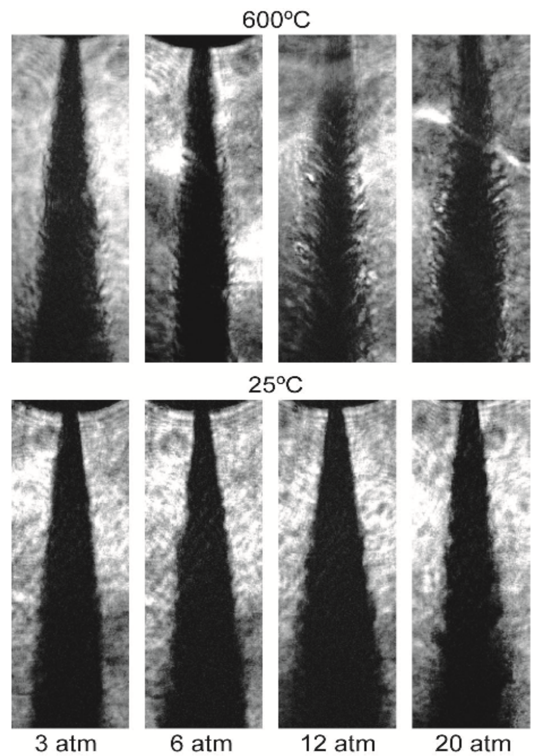

Figure 4. Ballistic images of a 1450 atm injection pressure dodecane spray captured at ~700 µs after start of injection. Images were taken in the pressure chamber filled with air. Images taken at 600°C show shedding of the liquid core at elevated pressure. Each image represents approximately 3 mm in spray length.

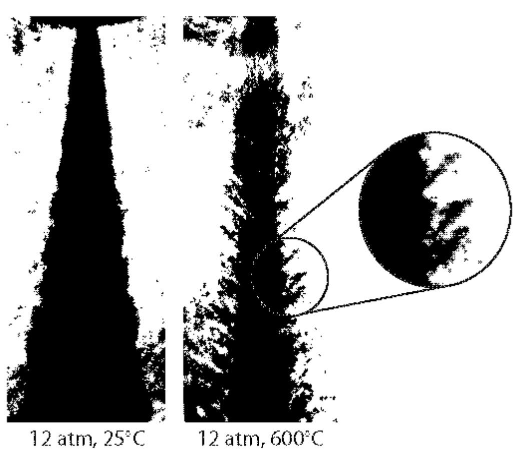

Figure 5. Binary ballistic images of dodecane sprays at 12 atm. Shedding is only seen at high temperature.

Significant differences in spray behavior were observed at elevated chamber temperatures and pressures. At low pressure and temperature, some smooth wave structure is apparent, but at high chamber pressure, sprays show significant signs of violent mass shedding from the spray periphery. This is clearly seen in Figure 5 where binary images at 12 atm reveal a wider spray at low temperature without shedding structures, but a narrower spray core with significant shedding at 600ºC.

A comparison of the spray cone angles of images taken at 20 atm and 25ºC and those taken at 20 atm and 600ºC reveal some interesting trends. Cone angle measurements were made of sprays over the entire injection event at the two aforementioned environmental conditions and plotted in Figure 6. The lower temperature spray reveals what appears to be a harmonic oscillation of the cone's angle, whereas the higher temperature spray initially oscillates but then settles to an almost constant angle. Interestingly, this temporal region corresponds directly with the existence of the 'fingerlike' structures caused by violent mass shedding. A similar trend is observed at 12 atm and 600ºC.

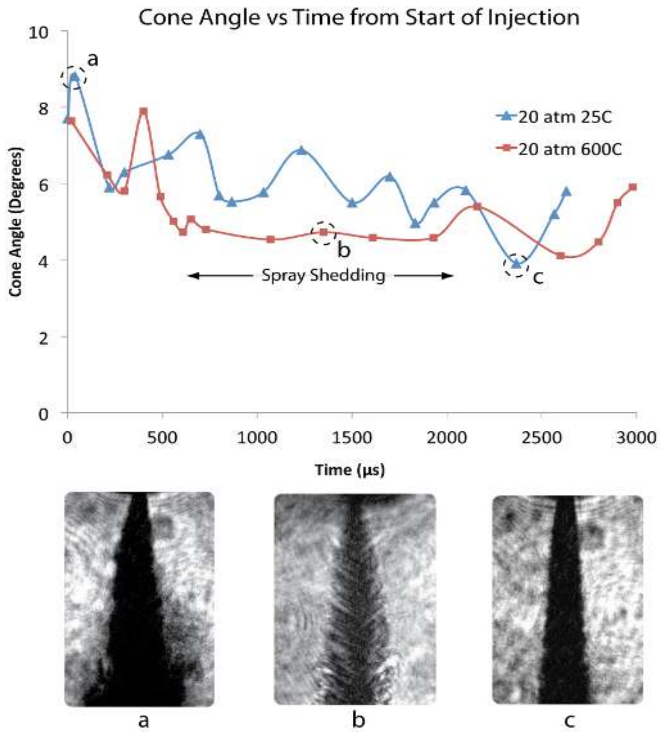

Figure 6. Measured spray cone angles as a function of time. Sprays were injected into a 20 atm environment at 25º and 600ºC. The smooth region of the 600ºC curve corresponds to the observation of spray shedding.

Summary and Conclusions

The first ballistic images of dodecane sprays into an environment typical of diesel pre-combustion demonstrate marked trends of cone angle fluctuation and significant mass shedding. To further the work presented here, modifications to the high-pressure facility are being made to reduce temperature variations and improve heating. Studies which aim at comparing different fuels and injector tip designs are planned in order to gain a fuller understanding of the fluid dynamics and mass transfer phenomena occurring in the near nozzle region. Additionally, investigation of near-nozzle spray structure will continue, with efforts to further characterize the observed shedding behavior. Specifically, it appears that the optical density of the spray seems lower during the period of time when the 'finger' structures occur, which may be indicative of evaporation and mixing within the spray cone. To further investigate this observation, application of techniques put forth by other research groups utilizing novel methods to probe and quantify optically dense sprays may prove fruitful.[4,8,9] Also, in order to improve the visual quality of future endeavors, efforts to enhance ballistic image backgrounds and resolution will take place.

Acknowledgements

This material is based upon work supported by, or in part by, the U. S. Army Research Laboratory and the U. S. Army Research Office under contract/grant number W911NF-07-1-0134. We are grateful for the support of the Army research office and Dr. Ralph Anthenien, technical program monitor.

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