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Effect of Properties/Injection Schedule on Fuel Spray Mixing

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Project Introduction

The DOE project for Co-Optimization of Fuels and Engines seeks to define both fuel properties and engine hardware to create cleaner and more fuel-efficient engines. Fuel spray technologies are central to this goal as the spray injection determines the combustible mixtures formed within the engine. Sprays are known to affect burn rate and efficiency, particulate formation and emissions, as well as temperature and engine knock sites. Computational fluid dynamic models must predict complicated interaction between plumes and vaporization to be useful as a design tool for industry.

Changes in fuel properties are expected to affect fuel delivery. While Co-Optima fuels may be selected for chemical criteria, such as high octane number rating, an understanding of how the physical properties affect spray performance is necessary to optimize fuel delivery. Many of the selected Co-Optima fuels have properties that are different than standard gasoline, requiring investigations for their performance. A new continuous-flow spray chamber facility has been completed, offering capability to control the pressure and temperature of the gases at engine-relevant conditions at the time of injection as well as a massive increase in data throughput. Direct-injection multi-hole gasoline sprays for different Co-Optima fuels are investigated in this chamber.

Objectives

Overall Objective

- Identify differences in fuel spray mixing, evaporation, plume-interaction, droplet atomization, and liquid film formation with respect to proposed candidate fuels.

Fiscal Year 2018 Objectives

- Complete new spray chamber facility with continuous-flow operation.
- Apply suite of high-speed optical diagnostics to measure vapor, liquid, plume-direction, and spray collapse at representative engine conditions.
- Use different injection durations and multiple injections to understand methods to limit liquid penetration and prevent wall impingement.

Approach

An optically accessible spray chamber designed for operation at pressures ranging from 0.25 bar (vacuum) to 150 bar, and gas temperatures from 300 K to 1100 K was installed in a new laboratory. A well-characterized gasoline fuel injector (Engine Combustion Network Spray G) was installed in a temperature-controlled port. The same injector is also used by Argonne National Laboratory for x-ray spray characterization. High-speed schlieren and extinction imaging were applied to measure liquid and vapor characteristics of the spray. New methods for post-processing line-of-sight diagnostics to reveal local plume characteristics were developed. The facility and diagnostics provide excellent capabilities for the study of fuel spray mixing and delivers key datasets important for CFD validation.

Results

A laboratory was reconditioned and a new high-pressure, high-temperature temperature vessel was installed as shown in Figure 1. This chamber utilizes a continuous flow of pressurized, high-temperature gases to an optically accessible test section. Fused-silica windows of 140-mm diameter act as the pressure window, while inner fused silica blanks act as a thermal barrier. Air, nitrogen, or air/nitrogen mixtures flow through heaters encased inside the pressure vessel and enter the spray test section at temperatures as high as 1100 K and pressures as high as 150 bar. The pressure vessel is insulated from the heaters and test section, and the vessel is water-cooled to maintain temperatures below 200° C, temperatures at which the duplex 2205 stainless material maintains strength. Exhaust gases are water cooled with a heat-exchange capacity matching the supply heaters. Fuel is delivered to temperature-controlled gasoline or diesel fuel injectors. Injections may be repeated after fuel vapor is scavenged downstream and a fresh charge of gas is available in the spray test section. The facility represents a major step forward in research capabilities, with an expected 300 × increase in data throughput compared to a premixed-burn style spray chamber [1].

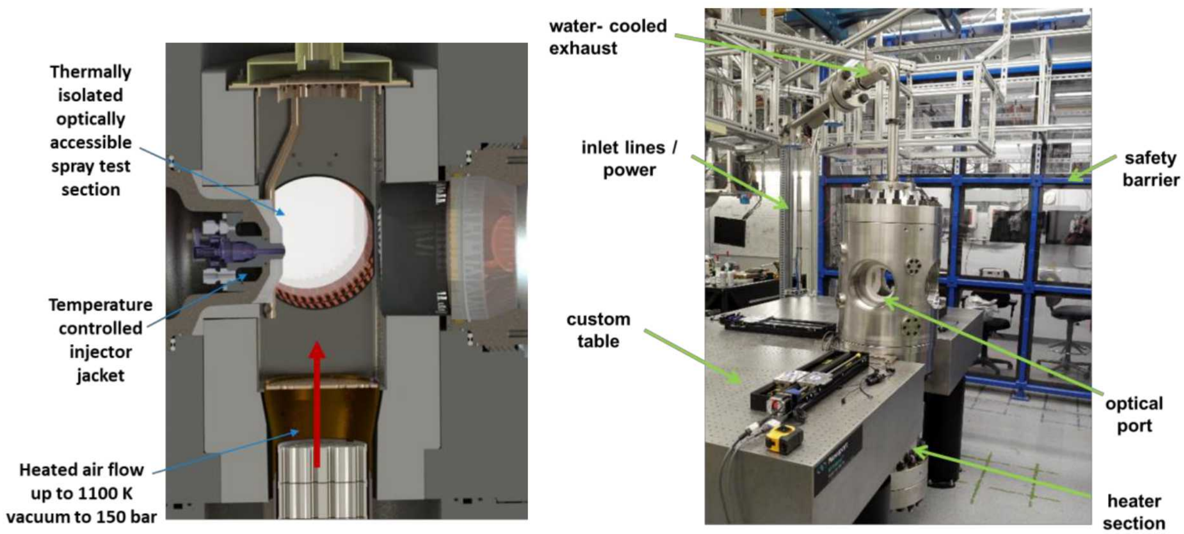

Figure 1. (left) Cross-section of continuous-flow heated spray chamber, with capabilities depicted, (right) installed in laboratory on optical table and behind operator safety barrier.

New experiments were designed to characterize the fuel spray mixing and evaporation processes. A reference fuel injector with 8 stepped holes, the Engine Combustion Network “Spray G” [2], was chosen for initial experiments because of the vast dataset developed for this particular injector and operating condition. Past work has shown that the interaction between plumes is complicated and difficult to predict [3]. Plumes may redirect from the manufactured drill angle, interact strongly, and cause the entire spray to collapse. The net effect is vastly different fuel delivery and wall impingement targeting depending upon the degree of interaction.

The manner of plume interaction and terminology for this process is depicted in Figure 2. The plume cone angle may grow because of internal nozzle flow behavior, but it also responds to changes in gas temperature and pressure, as well as the fuel itself. The plume growth and air entrainment creates intense aerodynamic forces that can redirect the entire plume far away from the drill angle. The resulting plume direction may change during the injection event [3], showing a sensitivity to the injection duration. CFD researchers that vary either plume direction or plume cone angle find that varying the cone angle provides better overall agreement compared to the various experimental results including gas and liquid velocity [3]. An experiment that could readily measure both the plume cone angle and plume direction would provide key information about the degree of interaction between plumes, and how these parameters depend upon fuel properties and injection duration.

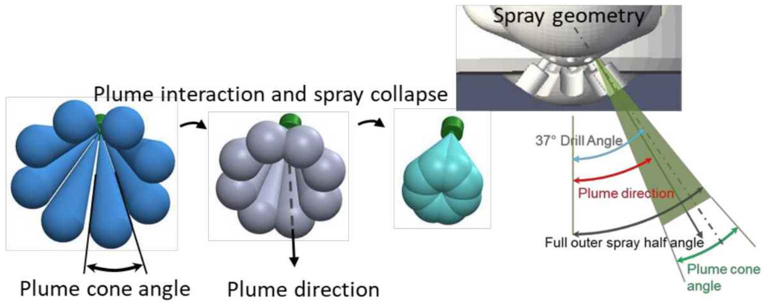

Figure 2. Schematic illustrating the geometry of Spray G, and the process of plume interaction and spray collapse.

The experiment utilizes two different high-speed imaging diagnostics, both line-of-sight measurements. The first is diffused back-illumination (DBI) imaging, applied to measure extinction from liquid. The second is schlieren imaging, applied to measure the outer envelope of the spray containing both liquid and vapor. The DBI diagnostic is sensitive to only liquid extinction, rather than vapor-phase beam steering, by nature of the diffused lighting and large collection angle. The diagnostic is used to measure the maximum axial and radial liquid penetration, for example, which is directly related to in-cylinder wall wetting and film formation. But by performing measurement with different injector orientations, it is also possible to identify the plume center at planes at different axial distances away from the injector, and thus the plume direction. The technique is demonstrated using synthetic spray liquid volume fraction (LVF) data as shown in Figure 3.

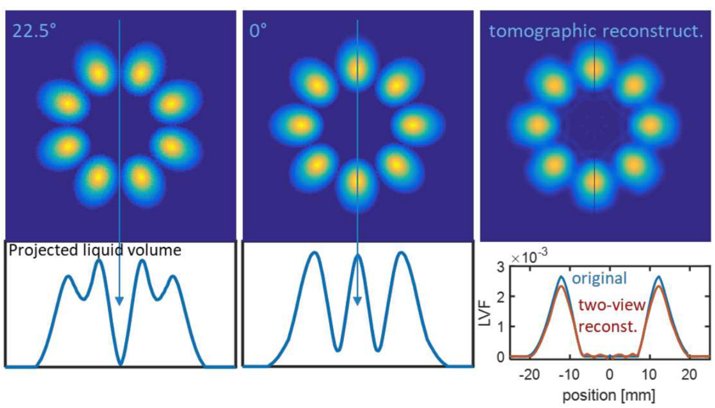

Figure 3. (Top) LVF simulations at axial distance cut plane of z = 15 mm. Middle is with injector at 0° rotation; left at 22.5° rotation. Right is tomographic reconstruction at 0° rotation. (Bottom left, middle) projected liquid volume, the integral of the liquid volume along a line of sight indicated at the top. (Bottom right) Profile of original LVF compared to tomographic reconstruction using projection data taken from only two views (0° and 22.5° rotation).

The synthetic liquid volume fraction data is from Gaussian-shaped plumes directed at the drill angle of the nozzle (37°). Sampled on a plane at a fixed axial distance from the injector, z, the plumes appear skewed towards the centerline, but this is a consequence of the distance of the plume relative to the hole origin. As shown in Figure 2, the left side of the plume (at a fixed z) has a shorter distance from the hole compared to the right side, and will therefore appear more fuel rich. The middle of Figure 3 shows the LVF distribution with the injector oriented in the primary position at 0° rotation where the entire spray is at its widest orientation. The left shows results with the injector in the secondary position at 0° rotation where plume pairs are in direct alignment with each other and the total spray is at its thinnest width.

The bottom left and middle simulates what is measured by line-of-sight extinction imaging at these two orientations. Experimental measurements in these two orientations demonstrate that it is possible to extract a plume direction from the measurement [3,4], although the data are seriously limited with respect to the number of injections and operating conditions where the plumes are distinct from one another. Without the usual data limitations, it is possible to collect images for many injections at many orientations using the new high-throughput spray chamber. To determine the minimum number of acceptable injector rotations, projection data from only two different orientations (as shown) were utilized to apply tomographic reconstruction of the spray footprint. A linear weighting function was applied to create artificial projections based upon different injector orientations. For example, the projection at 11° rotation is the mean (equal weighting) of the two projections shown in Figure 3, while the projection at 3° rotation is weighted 87% to that of the projection at 0° rotation and so forth.

The tomographic reconstruction using data from these two views given at the bottom right in Figure 3 shows nice agreement for plume center location and width of the liquid region, albeit the peak LVF and sharpness of features is degraded. Ultimately, the reconstruction is acceptable despite using only two different projection views. This exercise demonstrates the potential to use high-quality liquid extinction data to more exactly define the plume position in three-dimensional space. By coupling this method to high-speed imaging with the injector at several rotation positions, the primary outcome is identification of the plume direction at every instant in time during an injection event, including time after the end of injection.

Extinction imaging provides a measurement of plume direction, but as mentioned above, the plume cone angle can be the catalyst for plume interaction and redirection and it is critical for predictive CFD. Plume cone angle measurements are obtained using high-sensitivity schlieren imaging as demonstrated in Figure 4. These line-of-sight images show sensitivity to any refractive index gradient, including vaporized fuel or even shock waves propagating through the gas during the injection event. With the injector oriented at 0° rotation, the outer edge of plumes at the top or bottom of the images are exposed and distinct. In addition, the measurement is sensitive to vapor fuel to provide a true measurement of mixture fraction at the edge of the spray. If measuring only liquid, fuel-air mixtures at the periphery of the spray are not well represented, particularly for gasoline sprays at elevated temperature where fuel vaporization is rapid.

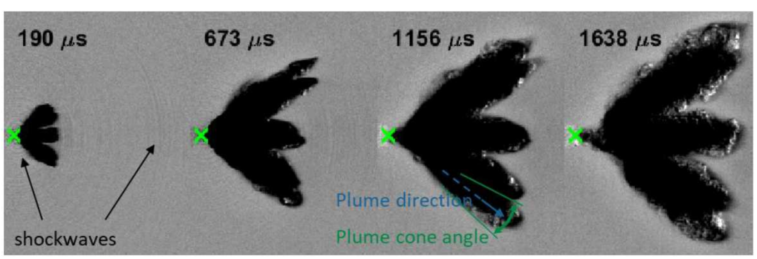

Figure 4. Time sequence of schlieren images from the same injection. Spray G fuel injector with iso-octane fuel and 0.8 ms injection duration. Injector is oriented at 0° rotation in the continuous-flow chamber. Time given relative to the start of injection.

As depicted in Figure 4, the exposed edge of the plume cone is measured with schlieren, which combined with the plume-direction measurement obtained using other DBI measurements, provides a measurement of the outer one-half of the plume cone angle. The measurement can be repeated for each plume by rotating the injector by 45° increments. Measurements are performed during injection as well as after the end of injection to characterize dynamics of plume interaction and vaporization after the end of injection, or with multiple injections.

Conclusions

Providing fundamental understanding of fuel spray mixing with alternative Co-Optima target fuels, a new spray chamber and new optical diagnostics have been developed. The datasets for liquid penetration, plume direction, and plume cone angle provide key data needed to improve CFD modeling of direct-injection fuel sprays. This work hastens the optimization of fuels and engines for low-emission, high-efficiency technologies. Key activities for FY18 include:

- Commissioning of a new high-temperature, high-pressure spray chamber facility with continuous-flow operation, capable of reproducing thermodynamic conditions at the start of injection for the entire engine operating cycle.
- Development of critical optical diagnostics for liquid penetration and motion of interacting plumes, including methods for tomographic reconstruction of plume position in three-dimensions throughout the injection event.
- Detection of the spray vapor envelope for quantification of the plume cone angle, which has been identified as a key driver for plume interaction and redirection and of fundamental importance for CFD prediction.

Together, the new spray chamber and diagnostics for plume cone angle and plume direction provide a powerful diagnostic to assess the effects of fuel properties. The diagnostics are currently being applied and analyzed for Tier-3-selected Co-Optima fuels.

Key Publications

Forthcoming

References

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Acronyms, Abbreviations, Symbols, and Units

CFD	Computational Fluid Dynamics
DBI	Diffused Back-Illumination
ECN	Engine Combustion Network
LVF	Liquid Volume Fraction