Evaporating and Combusting Vapor Penetration Session

Group Leader: Tim Bazyn (Caterpillar Inc.)
Contributors: Louis-Marie Malbec and Gilles Bruneaux (IFPEN), Lyle Pickett and Caroline Genzale (Sandia National Laboratory), Raul Payri, Jean-Guillaume Nerva, and Julien Manin (CMT), Tim Bazyn and Glen Martin (Caterpillar)

Summary of the Vapor Penetration Session

The focus of the vapor penetration working group for the ECN1 Workshop was to examine the methods and results for measuring the penetration of the evaporating or reacting fuel spray at the Spray A conditions.

Vapor Penetration, the distance from the nozzle to the leading edge of the fuel spray, is one of the fundamental measurements that has historically been used to quantify spray jets. It has been selected as one of the primary measurements for Spray A, meaning that spray penetration should be verified at spray A conditions before performing additional measurements. It is an easily observable and quantifiable phenomenon that is robust to experimental and processing methodology and it measures an important parameter in engine spray and combustion performance that provides an indicator of the mixing and spray processes.

The primary methods for measuring vapor penetration are shadowgraph and schlieren-based techniques, which measure the bending of light through the test section (2^{nd} or 1^{st} derivative of the index of refraction, respectively). These techniques use the same basic components – light source, large collimating and collecting optics, imaging lens, optional schlieren stop, and camera. Some variation in setups among the contributing institutions include chromatic and/or pulsed light sources, which can aid in rejection of combustion luminosity, and schlieren stop, with Caterpillar and Sandia using no stop, IFP using a disc for a dark-field schlieren arrangement, and CMT using an aperture for a bright-field schlieren arrangement. All the contributing institutions used an image processing routine developed at Sandia that looks at the texture of the temporal derivative of the series of images to define the spray region. Thus, the processing technique works best when measurable signals are achieved every where in the spray image, and saturated or dark regions are avoided. Additional processing is performed to smooth the edges, fill the holes, and add regions to the spray definition that were excluded because they were either very luminous or obscuring. This process involves sensitivity settings that must be matched to the optical set-up, currently in an ad hoc matching of the measured spray region with the apparent spray region. The maximum penetration of this spray region is reported as spray penetration.

Comparisons of the techniques showed that a properly set-up focused shadowgraph technique was sensitive enough to capture the edge regions of the spray, and that the additional sensitivity of a Schlieren set-up was not desired because it typically enhances the dark or bright regions that should be avoided. Also, temporal or chromatic filtering with a pulsed or monochromatic light source was preferred to eliminate combustion luminosity to avoid saturated regions for the same reason.

The sensitivity of cone angle and penetration was discussed, based on a discussion from Pickett et al. (SAE 2011-01-0686). While penetration measurements are relatively insensitive to optical set-up, cone angle measurements show a pretty significant sensitivity to optical setup and processing parameters. Comparisons with Rayleigh scattering measurements and the non-uniform mixing model of Musculus and Kattke (SAE 2009-01-1355) indicate that a high-sensitivity shadowgraph set-up captures the cone angle that corresponds to near zero fuel concentration. From this discussion, penetration will continue to be the primary measurement of bulk spray behavior due to its insensitivity to experimental method. However, future discussion of ECN contributors should address the addition of cone angle data to the ECN to capitalize on all the information that is available from spray shape measurements.

A review of the current results from ECN participants showed relatively good agreement among the groups. The data generally showed an agreement between the non-reacting and reacting cases up to the point of ignition, after which the combusting sprays showed an increase in penetration due to gas expansion from heat release. A few of the observed discrepancies were discussed:

- IFP observed earlier deviation between non-reacting and reacting conditions, explained by an earlier ignition delay due to higher ambient temperatures.
- CMT showed faster penetration after 2.5 ms after the start of injection due to a longer injection duration for their experiments, which was examined and verified with experiments of different duration at Caterpillar.
- Caterpillar observed slightly slower penetrations, which was explained as possibly a difference in the discharge coefficient or spreading angle, which agrees with spreading angle measurements which showed wider sprays. This is potentially explained by hotter orifice temperatures leading to changing flow conditions such as cavitation.

Data on the sensitivity of the spray penetration to density and injection pressure was also presented. This data provides some parameter sensitivity for model validation, one of the items mentioned in the discussion. Also, relatively good agreement was observed between Caterpillar and Sandia measurements for injection pressure sensitivity.

Summary of Experimental Uncertainty

Each institution provided an experimental uncertainty estimate, and this estimate is displayed in the slides on the graphs as light colored bands. The primary source of uncertainty is shot-to-shot variation. Each institution completed 5-12 repeats of the Spray A measurements leading to an uncertainty of the mean penetration length of 2-3%. Additional sources of uncertainty include optical resolution, nozzle position, and nonlinearity, but these sources represent less than 1% uncertainty. The variation in experimental conditions also creates some uncertainty in how accurately the experiments represent spray A conditions, and these values are provided in the presentation showing that most institutions matched spray A conditions within 1-2%.

Discussion Issues & Questions

The recommendations of vapor penetration methodology were agreed upon with little discussion. Discussion followed on the use of cone angle measurements in the ECN. The general thought was that experimental parameters would need to be standardized to enable cone angle measurement reporting, although consensus was not reached on how to do this. It was also discussed that additional sensitivity to key parameters should be measured to enable the correction of experimental data that deviates from the nominal condition as well as for model validation of parameter sensitivity.

Recommendations & Future Investigation

The recommendations for future ECN vapor penetration methodology were:

- Focused shadowgraph technique with high sensitivity
- Avoid bright, saturated flame regions (if possible) with chromatic or temporal filtering
- Use the available Sandia-developed processing algorithm of the texture of the temporal derivative as the spray indicator
- Define penetration as the maximum penetration of spray region
- Conduct future experiments with quantitative mixture fraction results to determine how this definition corresponds to mixture fraction

- Develop standardized experimental methods and processing algorithms for additional spray shape information that is available from data, such as cone angle