Spray A Liquid Length Measurements

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<u>Summary of the workshop session:</u>

This session presented Spray A liquid length measurements conducted at 4 contributing institutions: Sandia, IFPen, CMT, and Caterpillar.

Each institution conducted liquid length measurements by Mie-scatter imaging, an easily implemented liquid-phase detection technique commonly used by the diesel and gasoline spray research communities. An initial comparison of the Mie-scatter measurements at each institution revealed that the reported liquid lengths at the Spray A condition spanned approximately 3 mm: 8.2 mm (CAT), 10.6 mm (Sandia), 10.8 mm (CMT) and 11 mm (IFPen). Noting that this is a fairly substantial range, the session was primarily focused on discussing the potential reasons for such a variation in measured liquid length between the contributing institutions.

In the first portion of the presentation, one potential source of dispersion in the liquid length measurements was discussed: lack of consistency in the Mie-scatter experimental setup at each institution. An overview of the experimental setups revealed that each institution featured a unique combination of illumination source, direction and scattered light detection. A review of recent work at Sandia was presented to demonstrate the influence of these experimental variables on the quantified liquid length when performing Mie-scatter imaging. They applied a variety of illumination and imaging setups to Spray A. They found that the liquid length could be quantified up to 2 mm longer than their reported value of 10.6 mm by saturating the scattered light signal. They also found an increase of about 1 mm when the spray is illuminated from the head-on direction rather than from the side. These shifts in the quantified liquid length occur because the axial location and intensity of the peak scattering signal can change based on the illumination intensity, direction and scattered-light collection. Thus, when assigning a threshold or relative intensity cut-off to define the liquid length (typically 3% of the maximum signal), the axial location of that cut-off is dependent on the axial location and intensity of the measured peak scattering signal (which is dependent on the experimental setup). It was demonstrated that a scale factor can be applied to the data to bring the relative intensity behavior of the different experimental setups in line, but such a scale factor would be generally unknown.

The session also briefly discussed another potential source of dispersion in the liquid length measurements: facility-to-facility variations in ambient and/or fuel temperature. It was noted that based on work presented in the previous sessions, there may be differences in operating temperature at the 4 facilities. For example, IFP set their injector coolant temperature to achieve a nozzle temperature of 60°C prior to their premixed burn, while Sandia operated with a nozzle set-temperature of 90°C prior to the premixed burn. Liquid length predictions based on the Siebers mixing-controlled vaporization model were presented, showing that this 30°C difference can contribute to liquid lengths that are approximately 1 mm longer at IFP than at Sandia, consistent with a reported longer liquid length at IFP. Payri et al. (CMT) demonstrated a similar sensitivity to fuel temperature experimentally. Variations in ambient temperature are also expected to influence liquid length, but facility-to-facility variations in ambient temperature where not as readily apparent.

In the last portion of the presentation, a discussion ensued on alternative liquid length measurement techniques, based on light extinction. In addition to the collection of Mie-scatter techniques applied to Spray A, Sandia also applied two different light extinction measurement techniques: line-of-sight laser extinction along the axis of the spray and diffuse back-illumination imaging. As discussed during the session, these techniques may be preferred over Mie-scatter imaging because light extinction measurements are essentially self-calibrating. That is, they are based on direct measurement of an intensity ratio (I/I_o) and yield a measurement of optical thickness based on Beer's Law. Based on this premise, it was suggested that the use of an optical thickness measurement to define the liquid length might provide a less ambiguous metric for facility-to-facility comparison over the use of a relative Mie-scattering intensity, which is based on a peak signal that is sensitive to experimental setup. In addition, it was demonstrated that these techniques pose the promise of quantifying liquid volume fraction and/or droplet sizes since the measured optical thickness is dependent on these quantities. However, it was also shown that diffuse back-illumination imaging can be influenced by beam steering by the clipping of light rays at the collection aperture, yielding uncertainties in the measured optical thickness and making the lowest levels of optical thickness undetectable.

<u>Discussion items from the workshop:</u>

- Based on the difficulties presented in unifying Mie-scatter liquid length measurements, the group generally agreed that a light-extinction technique should be considered for recommendation as the standard ECN liquid-length measurement technique.
- A key consideration expressed by many members of the ECN was the importance of selecting a liquid length measurement technique that could be easily implemented at each of the facilities.
- It was also pointed out that consistency between the measurements is likely to be of more importance for this task than quantitative accuracy. The primary goal of these measurements is to verify that each facility has reached the Spray A

condition, not necessarily to provide a quantitative measure of liquid length for model validation

- Though beam steering present in the back-illuminated extinction images may contribute to uncertainty about the precise location of liquid length, the group believed that a comparison of the extinction drop-off behavior just upstream of the liquid length could provide a more robust comparative measure than Mie-scatter imaging.

Recommendations:

- The standard liquid length measurement to verify the Spray A condition should be performed using diffuse back-illumination at 532 nm (green LED).
- A comparative measure should be defined in order to assess the consistency of the measurement at each institution. A strict threshold based on optical thickness may not be appropriate since beam steering prevents detection of the lowest optical thickness levels near the spray tip. The optical thickness "drop-off" just upstream of the spray tip offers a potential metric. This metric should be assessed once several contributing institutions have completed back-illumination measurements of Spray A.
- The influence of beam steering on the measured optical thickness should be assessed.
- Groups wanting to use this data for validation of CFD models should be made aware of the limitations of this measurement data for use as a quantitative measure of the liquid length. A further assessment of beam steering effects on the measured optical thickness and the potential to measure low levels of optical thickness near the spray tip is needed.
- A rigorous methodology for setting fuel delivery temperature is necessary to eliminate this source of facility-to-facility variation in the liquid length.

Spray A Liquid Length Measurements

ECN 1: First Workshop on Spray Combustion

Ventura, CA – May 13-14, 2011

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IFPen

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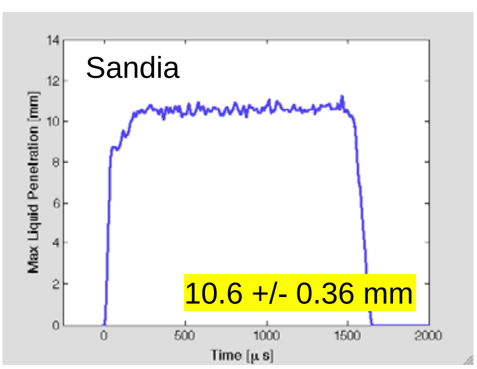
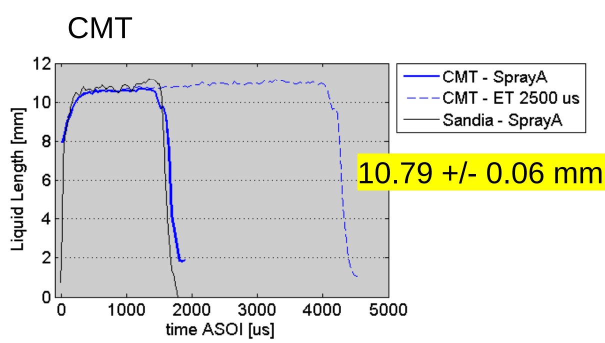
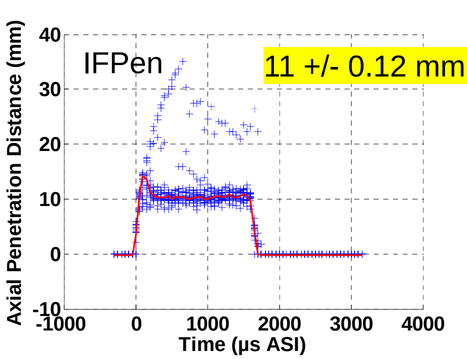
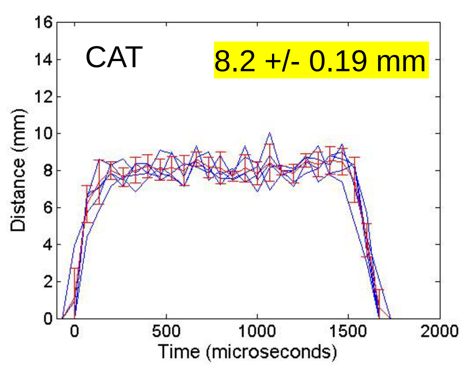
CAT

ECN groups reporting so far show a rather wide range of liquid lengths, spanning ~ 3mm.



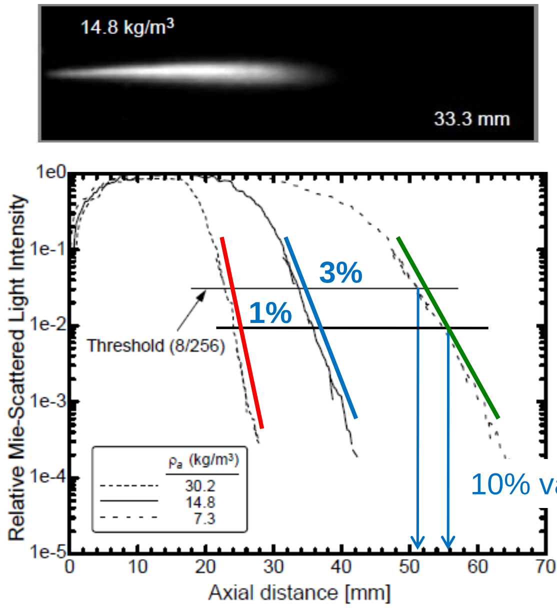






How can we unify liquid length measurements across facilities for Spray A?

Siebers SAE 980809

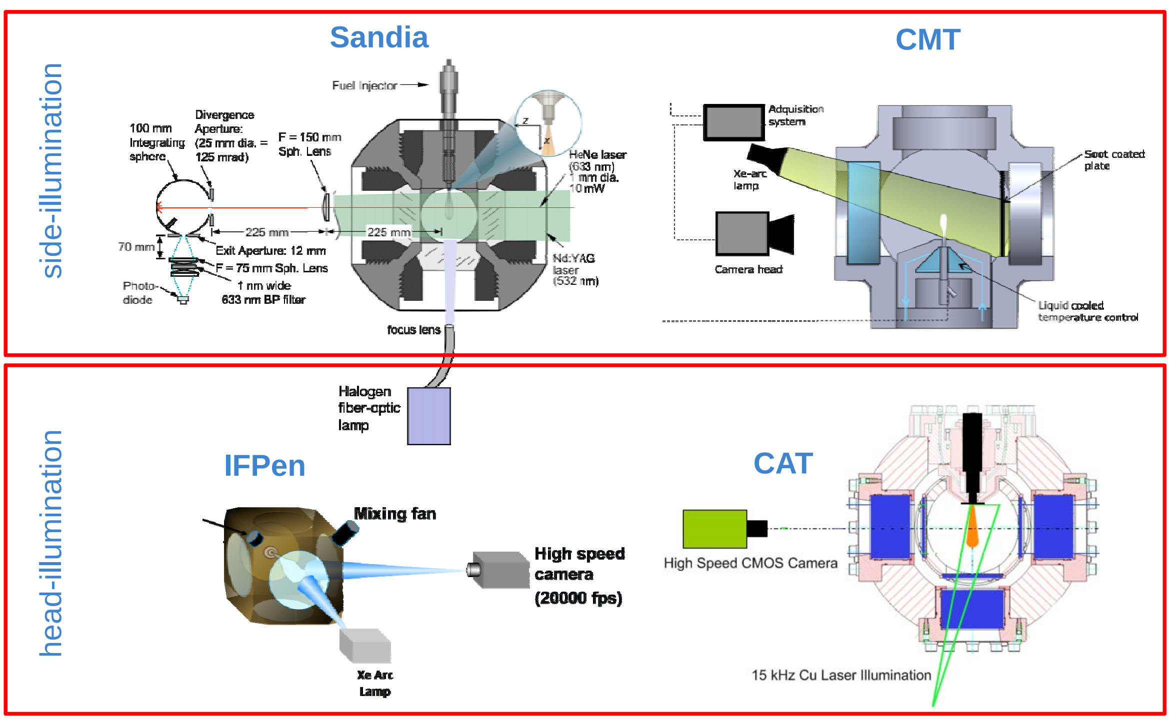


Factors that may influence the <u>quantified liquid penetration:</u>

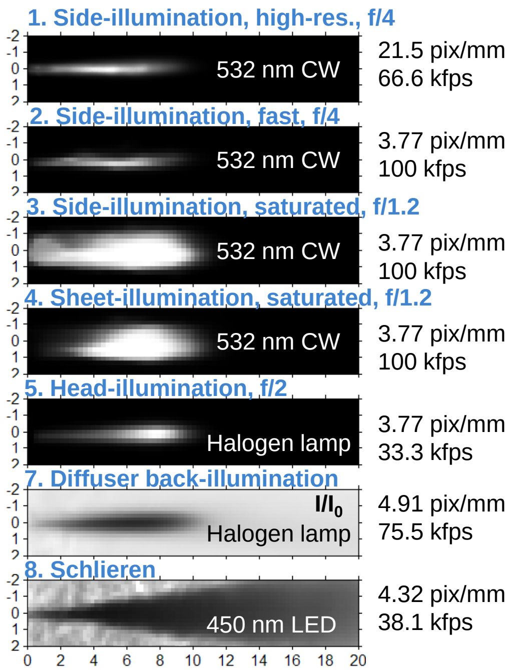
1. Threshold sensitivity
2. Ambient/Fuel conditions
3. Illumination method
4. Imaging setup
5. Processing method

10% variation in reported liquid length

Experimental setups for liquid length measurement differ at each institution.



At Sandia, we made an effort to understand potential differences arising from exp. methods.



We see significant differences in the shape of the illuminated spray when different lighting and optical setups are employed.

These differences motivate a need to evaluate light scattering based measurements from a more fundamental perspective.

Pickett et al., ILASS 2011-111
Monday 5/16, 9:25 am

Some good news: We don't see significant changes in relative light scattering behavior with changes in image spatial or temporal resolution.

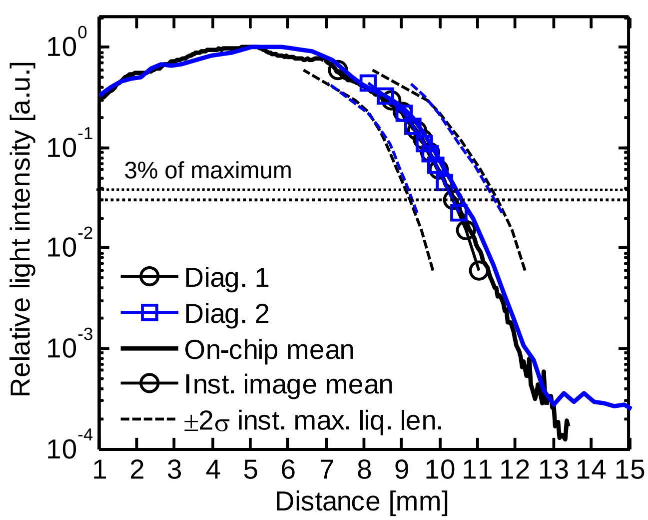
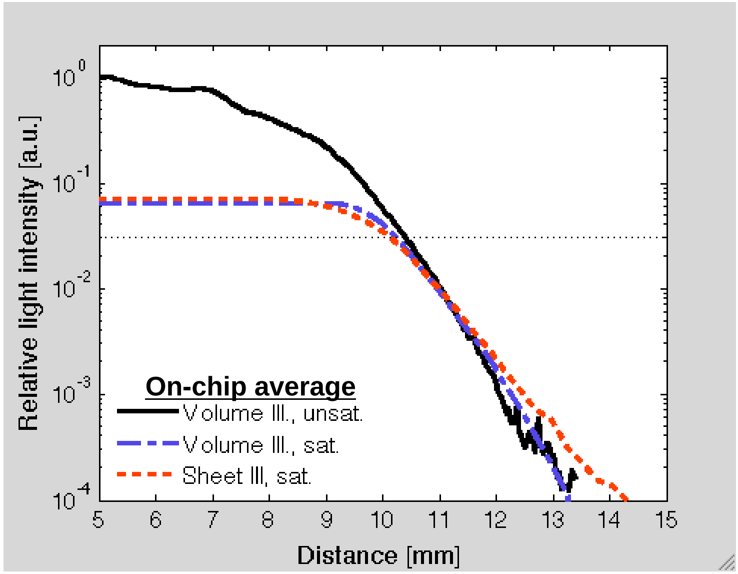
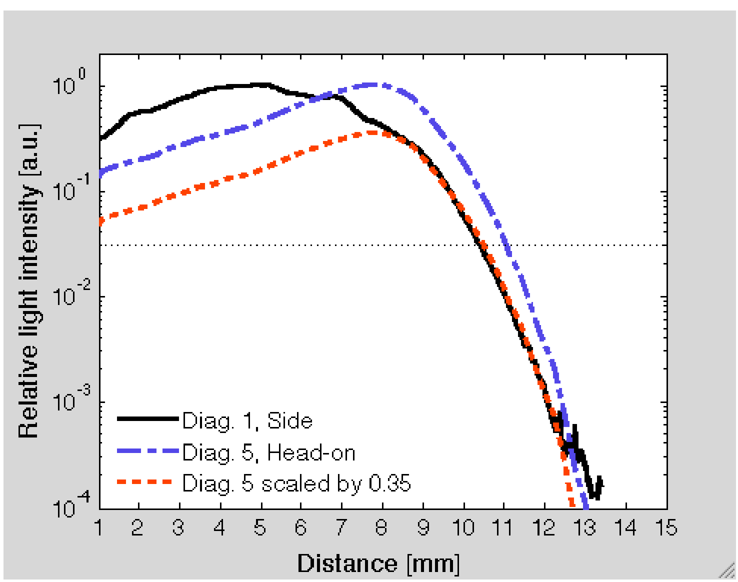


Image saturation will influence "relative" intensity: this needs to be considered.



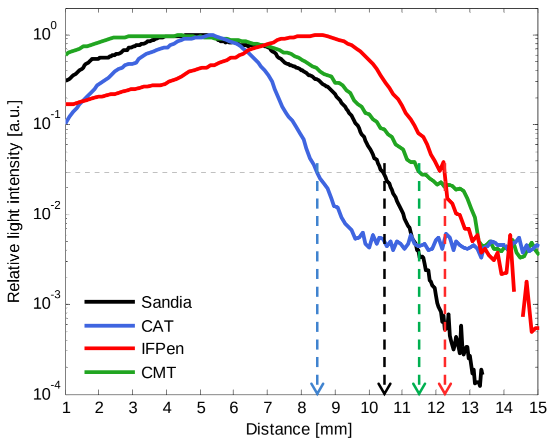
- A simple scale factor brings intensity drop-off curves together, but the unsaturated maximum intensity must be known to equate the two measurements.

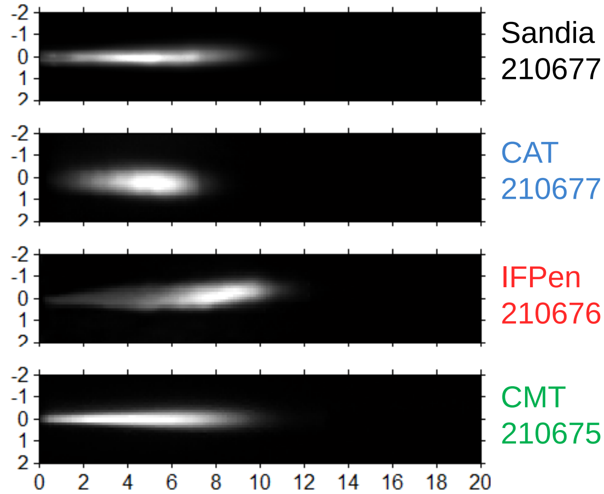
Lighting arrangement also affects intensity drop-off behavior due to attenuation along illumination path.



- A simple scale factor again brings intensity drop-off curves together
  - Similar to saturation, the scaling accounts for the peak intensity that would be reached if not for attenuation due to illumination path

Comparison of ECN intensity drop-off at each facility does not yield a clear picture.

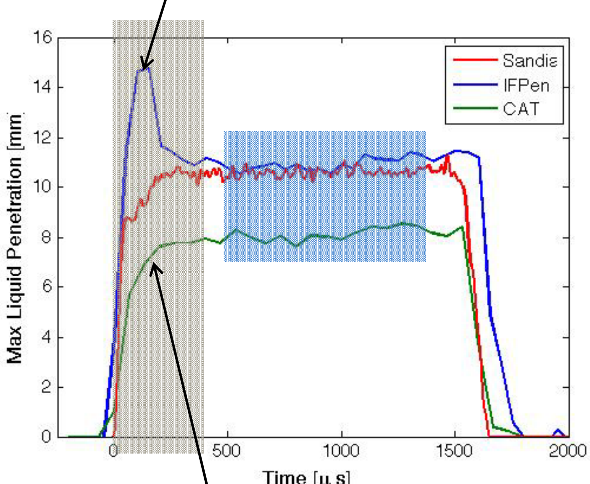


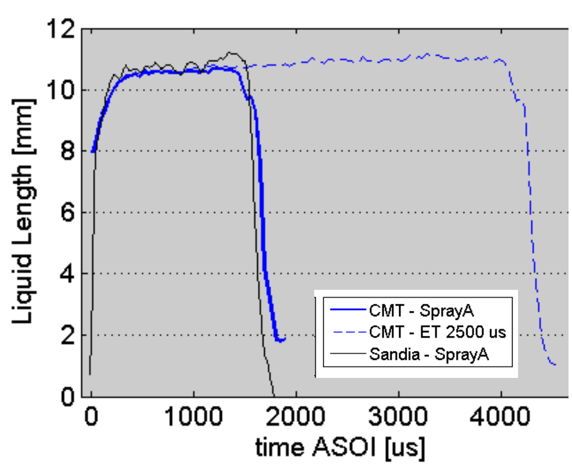


- Sandia now at 10.2 mm (10.6 mm on website for out-of-focus data)
- These numbers are a bit different from those presented earlier
  - Time-average vs. on-chip average
  - Processing methods?
- Application of simple scaling factors does not collapse these curves
  - Factors other than experimental setup are likely at play

The early transient behavior requires consideration, but is largely consistent between facilities.

likely condensation effect

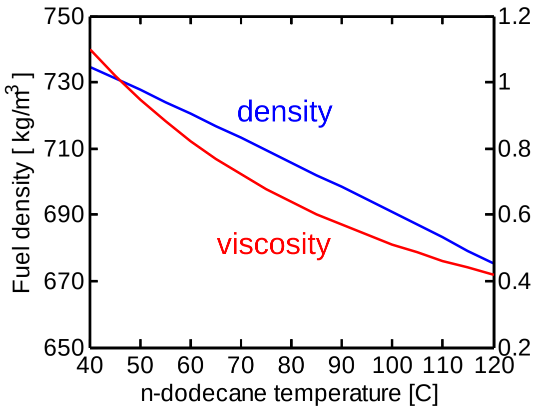


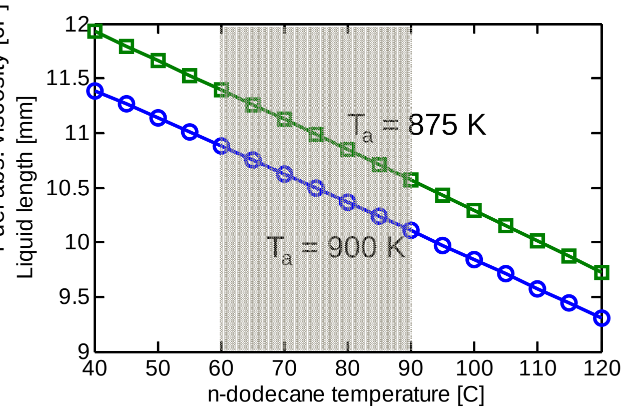


fuel temperature transient?
Injection rate transient?

Up to a 30K difference in fuel temperature is likely between IFP and Sandia.

n-dodecane fuel properties (1 atm)

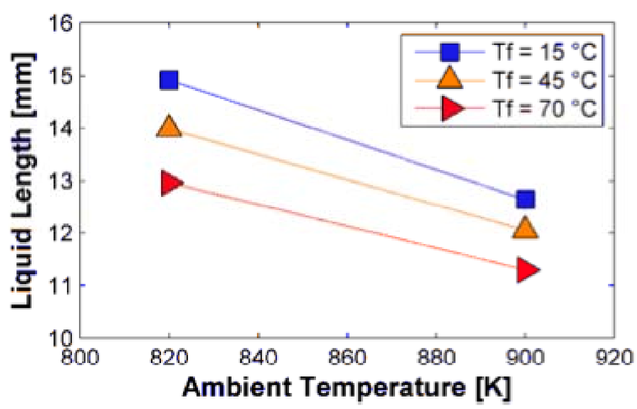




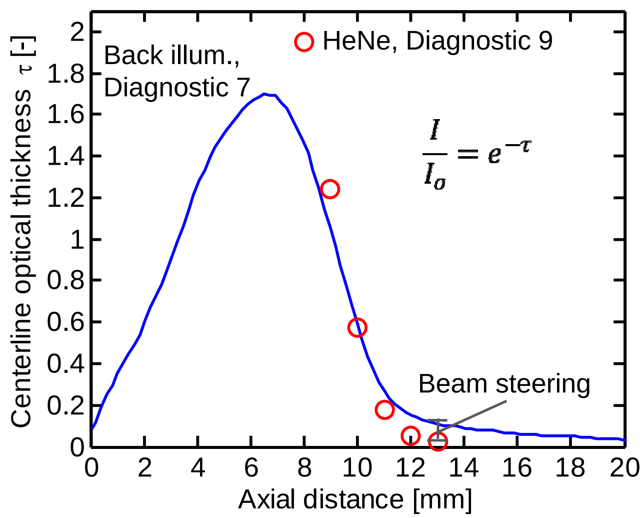
Depending on ambient variations, there may be up to 1 mm increase in liquid length for 60°C fuel temperature

CMT shows a similar measured result.

Payri et al., ILASS 2011-163



Line-of-sight extinction may offer a more consistent liquid length measurement since it is inherently based on relative intensity.



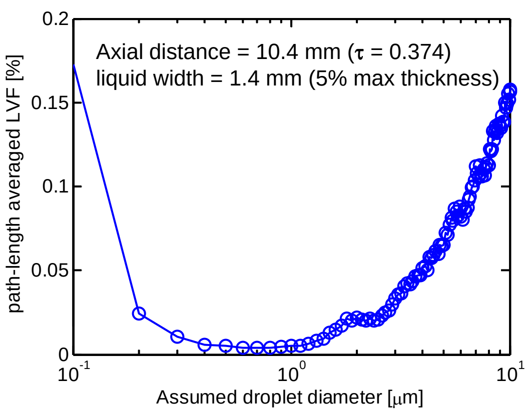
Recommendations for reaching a common Spray A liquid length measurement

- We will likely need to define a standard measurement, illumination and light collection technique since peak intensity and relative threshold will be influenced by attenuation along light path. This could be a challenge.
- We need to fully understand and quantify the fuel and ambient temperatures in our facilities.
- We will also need to unify processing methods and techniques (IFP uses axial intensity only, CMT uses a different background correction, …).
- The injection transient needs to be considered. We may want to define a specific time window ASOI for quantifying the liquid length.

Recommendations for reaching a common Spray A liquid length measurement

- Based on our experience with different measurement techniques at Sandia:
  - Unsaturated images are necessary to define a consistent relative maximum.
    - Once defined, saturated images can provide increased sensitivity to lower light levels.
  - Head illumination features a higher sensitivity and a steeper intensity drop-off.
    - Less sensitive to relative intensity thresholds.
    - Could be easier to implement in multiple facilities.
  - A line-of-sight extinction measurement may be the preferred method since the calibration intensity is inherently built in to the measurement.
    - No intensity scaling ambiguity.
    - Line-of-sight access needed only.

Line-of-sight extinction measurements can also help provide an estimate for LVF at the LL.



$$\frac{I}{I_o} = e^{-\tau}$$

$$\tau = \int_{-Z_\infty}^{Z_\infty} C_{ext} N dz = C_{ext} \int_{-Z_\infty}^{Z_\infty} \frac{LVF}{\pi d^3/6} dz$$