ECN 4: New standard for high temporal DBI extinction imaging

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Abstract: An optical setup has been developed for diffused back-illumination imaging of liquid and soot extinction with high temporal capabilities. It has been specifically designed to isolate attenuation by absorption/scattering from light displacement by refractive gradients through a heated and pressurized environment. The design criteria have been determined from a conceptual description of beam-steering effect on quantification using simple ray tracing. These criteria are used to optimize for collection efficiency for high temporal capabilities. The improvements observed show that beam-steering effects on quantification is suppressed down to within the noise of the camera, thereby higher sensitivity and accuracy of soot extinction and liquid penetration measurements is achieved.
• Quantitative soot volume fraction and qualitative liquid penetration measurements at high temporal resolution

![Graph showing extinction vs. axial distance for different samples.]

**Previous DBI extinction imaging setup**

- Diffuser
- Field lens
- Image plane
- Camera

- Quantitative soot volume fraction and qualitative liquid penetration measurements at high temporal resolution

- Soot extinction spray A
  - std conditions. 630nm LED old DBI setup

- Liquid penetration spray A
  - std conditions w/ 0% O2. 450nm LED old DBI setup
Eliminating beam-steering

• Laser extinction requires wide collection angle to account for beam steering

• Image extinction requires wide angular distribution of the light to suppress beam steering
Refracting media can have a mix of many interactions with the incident light

1. Snell effect (modifying effective focal length)

2. Oblique Snell effect (Translation of the collection cone)

3. Slanted Snell effect (shifting the optical axis)

4. Lensing effect (modifying focus/expansion)

How to make undesired refraction effects invisible:

1. And 2. Spatial homogeneity of illumination across the source

3. Even angular distribution wider than the collection angle

4. Cannot be corrected with diffused lighting
Dimensioning DBI setup

- Collection efficiency is important to promote high temporal resolution capabilities
- Spreading angle of large engineered diffuser should be 1.5 time the collection angle
- Large collimated beam needed for diffuser to work optimally
Measuring angular distribution

• 1D measurement

- Imaging plane
- Mechanical rotating base
- Variable aperture

![1D measurement diagram](image)

- 1D measurement graph

• 2D measurement

- Camera chip
- Fixed aperture at imaging plane

![2D measurement diagram](image)

- 2D measurement graph

\[ \tan^{-1}\left(\frac{\sqrt{x_p^2 + y_p^2}}{L}\right) \]

• Old setup

- Collection efficiency as a function of angular distribution

• New setup

- Ray tracing

- Old setup graph

- New setup graph

September 2015
Camera issues

- Fixed pattern noise is affected by the camera readout
- Noise level restored after one dark frame

\[
\text{KL} \downarrow \quad -\ln\left(\frac{I^*}{I_0}\right) < -\ln\left(\frac{I}{I_0}\right)
\]

- Correction brings dark up to \( BG_0 \)

\[
\text{KL} \uparrow \quad -\ln\left(\frac{I^*}{I_0}\right) > -\ln\left(\frac{I}{I_0}\right)
\]

- Correction brings \( BG_0 \) down to \( BG_1 \)
New DBI setup performance

- Quantification is affected when beam-steering effects introduce erroneous extinction

- Beam-steering effects smear out the sharp contrasts of the dense liquid vapor boundary
Checklist

• Report optical arrangement with distances, components and sizes
• Measure lighting characteristics with either 1D or 2D arrangement

Recommendations:
1. Angular distribution should be chosen to be 1.5 times the collection angle and be homogenous across the image plane.
2. Spatial intensity should not fall more than 20% from the center to the periphery of the image plane.
• Report camera corrections made in post-processing and camera software corrections used
Summary

• The need for a new standard DBI setup is realized
• The effect of beam-steering when spatially resolving extinction measurements is systematically identified
• From these effects, the lighting criteria for a new DBI setup are established
• A DBI setup dimensioned wrt ideal lighting and high temporal resolution capabilities, is proposed
• Issues with the high speed camera when performing high temporal extinction imaging are addressed
• The performance of the setup reveals significant improvement in suppressing beam-steering while maintaining high temporal capabilities
• Sensitivity of extinction imaging measurements is increased and errors associated with beam-steering are suppressed within the noise of the measurement
ECN 4: Spray C and D liquid and vapor penetration

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Abstract: Liquid and vapor penetration measurements are performed on a cavitating and non-cavitating automotive fuel injector (Spray C and D). The measurements are performed simultaneously using DBI and Mie scattering to image liquid phase and focused shadowgraph to image vapor phase in a dual line of sight accessible constant volume combustion vessel. The aim is visualize qualitatively the effect of cavitation on fuel spray characteristics. The experiments were performed under non-reacting and reacting Spray A std conditions. Results show that vapor phase penetrates faster and liquid phase longer for non-cavitating nozzle. The main reason being that the spray angle is wider for cavitating nozzle. There are some uncertainties as to what causes a wider spray angle and if it is cavitation related, as there are several other factors that may be responsible for this phenomena. CFD modelling can help answer questions about the origin of the wider spray angle.
Break-up of liquid sprays

- Primary break-up: Stripping of ligaments and droplets from the intact liquid core
- Secondary break-up: formation of spherical droplets.
- These break-up processes are confined close to the nozzle exit.
- Studies have shown that instabilities caused by cavitation within the nozzle, greatly promotes this break-up process.
Spray C and D Nozzles

Spray C 210037

K-factor 0
\( d=0.2\text{mm} \)

Minimum diameter the same
\( d_{\text{min}}=0.186\text{mm} \)

K-factor 1.5
\( d=0.18 \)

Mass 43.2mg/inj
Duration 2.5ms

Spray D 209134

Mass 50.75mg/inj
Duration 2.5ms
Experimental methods

• High speed jet penetration measurements with focused shadowgraph technique
• High speed liquid penetration measurements with new standard DBI technique
• Liquid penetration measurements with Mie scatter technique at 90 degree solid angle
• All measurements were made simultaneously for every injection event
• Results are based on 10 injections with each nozzle at the standard reacting and non-reacting Spray A condition
Experimental setup

- Pinhole aperture
- Parabolic mirror
- Collimated beam
- 50mm f/1.2 lens, 500D close-up lens and 514.5nm BP filter
- Diffused light collection cone
- Saffire windows
- 100mm EDC15
- 1' EDC30
- 630nm LED 1µs pulse width
- 520nm LED 1µs pulse width
- Fresnel lens
- 60/40 Beam splitter
- 50mm f/1.2 lens and 600nm SP filter
- Phantom V7.1, 50kfps, 9.7µs
- DBI liquid penetration camera
- Photron SA-X2, 150kfps, 2.5µs
- Mie scatter liquid penetration camera
- Photron SA-X2, 150kfps, 5.65µs
- Shadowgraph vapor penetration camera
- Constant volume combustion vessel
- Mixing fan
- No knife edge on Schlieren focus
- Spray
- Parabolic mirror
Results Non-reacting

Density = 22.8 kg/m³
Fuel = n-Dodecane
\(P_{inj} = 1500\) bar
Temperature = 900 K
\(x_O_2 = 0\%

- Spray D Liquid penetration (DBI)
- Spray C Liquid penetration (DBI)
- Spray D Liquid penetration (Mic)
- Spray C Liquid penetration (Mic)
Results Non-reacting

Density = 22.8 kg/m³
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- Spray D Liquid penetration (DBI)
- Spray C Liquid penetration (DBI)
- Spray D Liquid penetration (Mic)
- Spray C Liquid penetration (Mic)

Axial distance [mm]

Axial distance [mm]
Width of liquid spray

- Onset of boundary instability closer to the nozzle for Spray C
- Spray C looks to have a virtual origin further from the nozzle

- Liquid/vapor boundary is wider and more deformed closer to the nozzle for Spray C
- Oscillations of the boundary are stochastic and show no distinct frequency
- Width of spray correlates with magnitude of oscillations at the boundary
Effect of cavitation

• Mixing based liquid length model accurately predicts the difference in liquid length
• Spray angle and contraction area source of difference in liquid penetration
• Is the difference cavitation related?
• Spray C geometry is slightly diverging
• Lower effective diameter also promotes divergent flow
• Difference may be due to mismatched mass flow
• CFD modelling of internal flow and liquid penetration can help answer these questions
• Vapor penetrates at a slightly higher rate after ignition
• Spray angle becomes wider after ignition
• Liquid length has less tendency to increase over time
Sandia & CMT data

- Large deviation between liquid penetration for both C and D nozzles
- Liquid length increases more with time for CMT measurements
- Vapor penetration measurements are similar
Summary

• Liquid and vapor penetration measurements have been performed simultaneously with Spray C and D.
• Good agreement between DBI and Mie liquid penetration measurements.
• Differences between Spray C and D are mostly caused by difference in spray angle, and it is uncertain as to why Spray C is wider.
• Reacting measurements show that thermal expansion slightly accelerates vapor penetration and liquid penetration does not increase over time due to hotter entrained gases.
• More work needed in the comparison between institutions as large deviations seem to stem from differences in nozzles.
• Vapor penetrates at a slightly higher rate after ignition
• Spray angle becomes wider after ignition
• Liquid length has less tendency to increase over time
Components and function

- High speed camera
  - Photron SA-X2

- State of the art LED driver technology
  - TIR LED collimator
  - Sandia 614 LED driver

- Optics promoting high collection efficiency
  - Engineered diffuser

- Filtering
  - Band-pass filter
  - Neutral density filter
Camera characterization

- High speed camera sensors are sensitive to ambient conditions and operation characteristics

$$KL = -\ln \left( \frac{I}{I_0} \right)$$

- Pixel response curve needs to be corrected for
Dimensioning DBI setup

- Collection efficiency is important to promote high temporal resolution capabilities
- Diffusing angle should be chosen so as to not overfill the Fresnel lens
- Spreading angle of final diffuser should be as narrow as possible