Engine Combustion Network

Topic 3: High-speed mixing measurements

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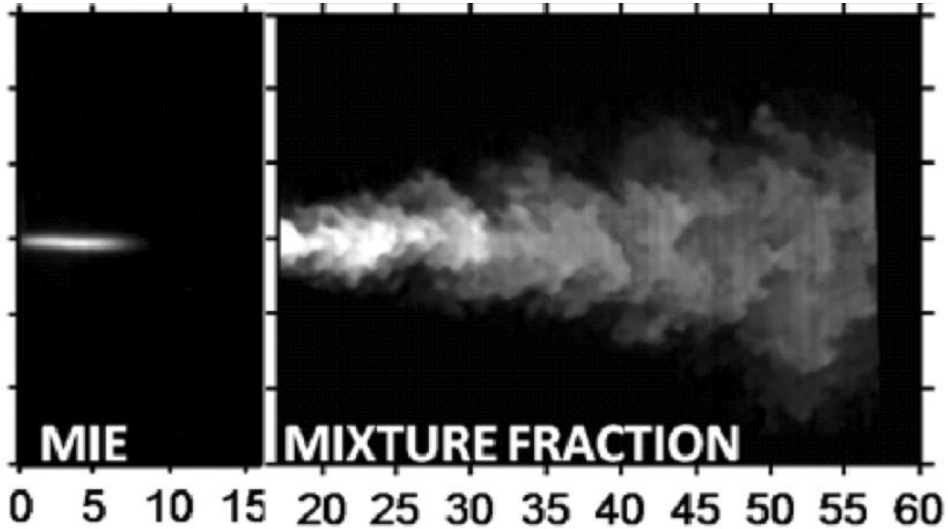
Motivation and previous work

- Mixture preparation is considered the back-bone of combustion
- Mixing experiments are difficult under relevant thermodynamic and injection conditions like Spray A
- Mixing measurements at Spray A have been performed at Sandia a few years back
  - But transient information has been lacking mainly due to equipment limitations
  - Other issues effectively limited the optical resolution of the system



Pickett et al. SAE Int. J. Engines 2011

- Despite these limitations, this dataset has been used extensively for model validation beyond the thermal engine application boundaries
- New equipment such as high-speed lasers or imaging systems can extend experimental capabilities for mixing measurements under relevant conditions
  - Transient mixing field is a preliminary step towards predicting ignition
  - Variance quantification is another important parameter to turbulence modeling

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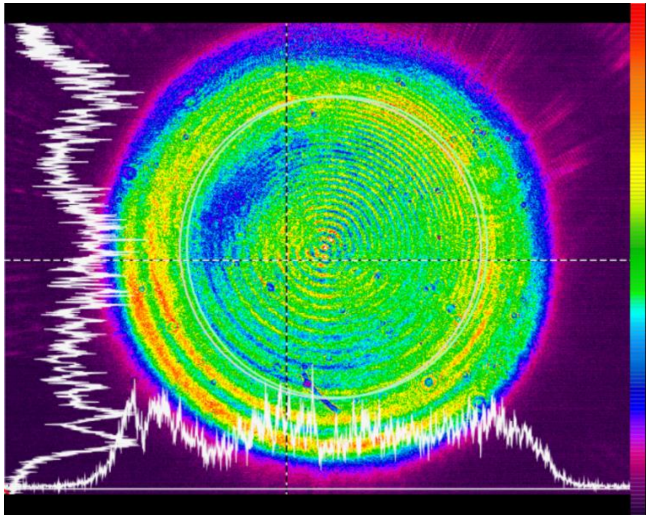
High-power pulsed burst laser system

- High repetition rate seed laser followed by three multi-pass amplification stages
  - Q-switched diode-pumped Nd-YAG seed laser operated at 100 kHz
  - Diode-pumped resonators with 2 and 5 mm diameter rods for the first two stages (Nd-YAG)
  - Final stage uses 10 mm rods in two legs to reduce beam energy on amplifiers
  - Over 70 mJ/pulse capabilities (7 kW)
- Relay imaging of the beam and spatial filtering done throughout the laser path
- KTP crystal used on both legs for harmonic generation (532 nm)
  - Single leg pulse energy was enough
  - Relay imaged to sheet-forming optics
  - 20-mm wide laser sheet (approx. 15 to 35 mm from the injector)

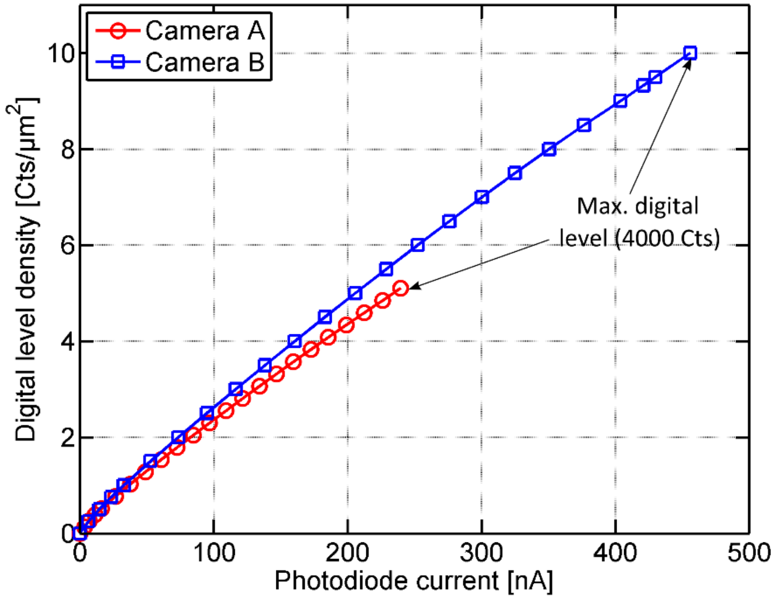
Parameter	Quantity
Frequency	100 kHz
Burst duration	5 ms
Pulse width	4 – 8 ns
Wavelength	532 nm
Pulse energy	15 mJ
Polarization	Horizontal



Laser design team: Scott Bisson, Brian Patterson and Jonathan Frank

High-speed imaging system

- The design and development of a high-speed imaging system was investigated
  - But CMOS-based high-speed cameras evolve too quickly to justify designing and building a specific imaging system
- The selected camera features higher light sensitivity and smaller pixels than the competition
- Raw images are corrected for intensity linearity and lens vignetting for accurate signal quantification prior to post-processing



Parameter	Quantity
Framerate	100 kfps
Resolution	384 x 264 pix^2
Camera lens	58 mm – f/1.2
Close-up lens	2 diopters
Scale factor	78 µm/pix
Spectral filter	532 nm (BP 10 nm)

- Camera mounted perpendicular to the jet to acquire Rayleigh scattered signal through the top-mounted optical access of the vessel
- Heat-shielding and liquid cooling system were implemented to keep the lens cooled to avoid thermal stress and image deformation

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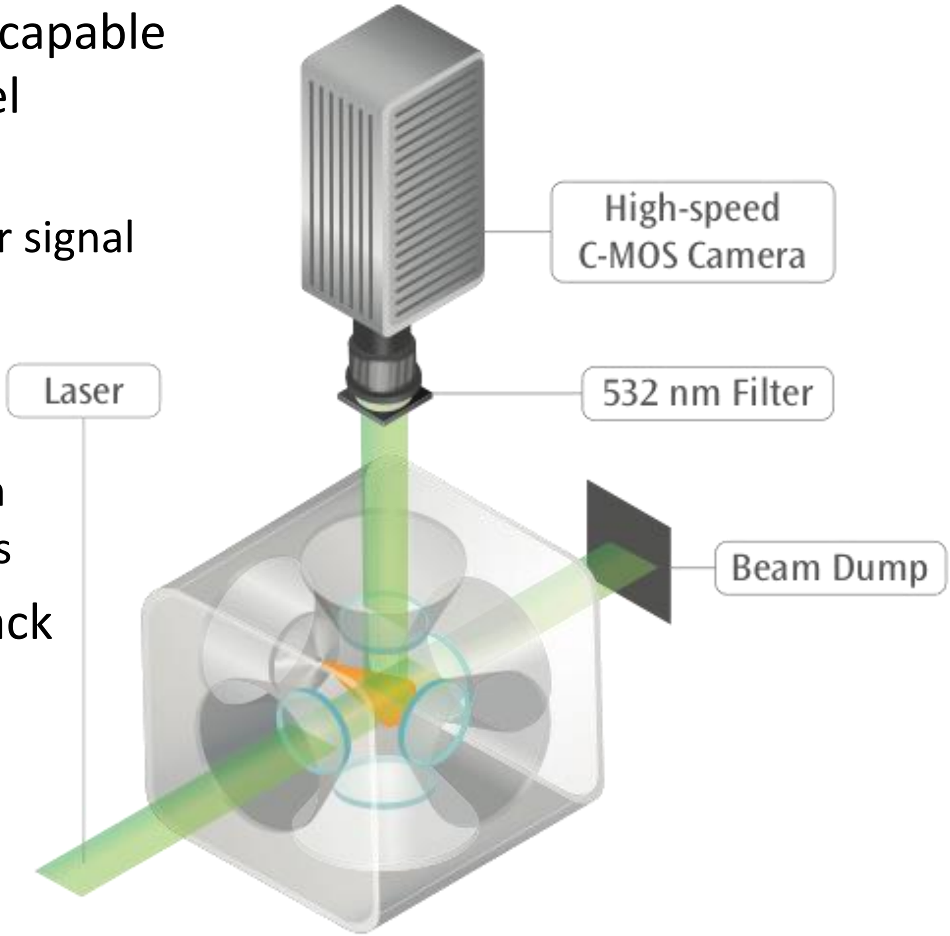
Spray vessel and conditions

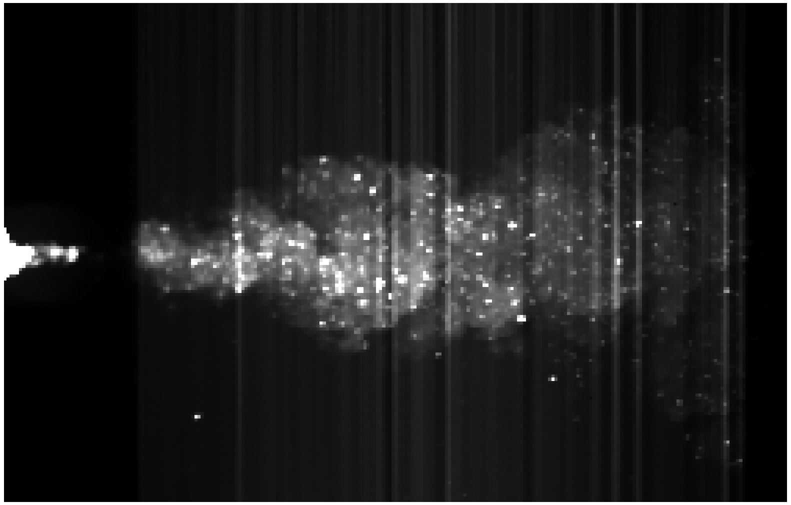
- High-temperature and high-pressure capable optically-accessible combustion vessel
  - 35 MPa – 1800 K peak conditions
  - Sapphire window for Rayleigh scatter signal acquisition
  - Fused-silica window slits for laser input and output
  - Recessed and baffled window design with AR-coating to reduce reflections
- Vessel surfaces coated with matte black paint to minimize surface reflections

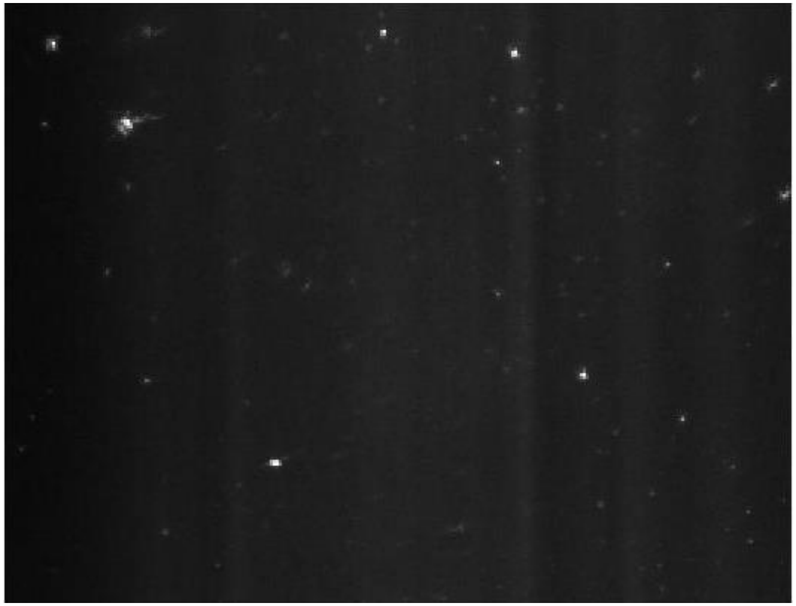


- Spray A inert conditions were tested:
  - Ambient temperature: 900 K
  - Ambient pressure: 6.0 MPA
  - Environment composition: 90 % N_2, 6 % CO_2, and 4 % H_2O, 0 % O_2
  - Spray A injector (serial # 210370) at 150 Mpa, 1.5 ms injection duration

High-precision fuel system

- Rayleigh scatter imaging aims at quantifying molecules, and is dependent to the sixth order on particle size
- Liquid droplets or particles in the ambient or fuel will contaminate the signal from the probed molecules
  - Past experiments suffered from particle contamination from the fuel
  - Solid particles from nozzle deposit have been observed in the head of the spray





- New high-pressure fuel system with high-precision syringe pump
  - Fuel has been filtered through 100 nm membrane filters to remove particles
  - High-pressure in-line 0.5 µm filter to stop solid contaminants from the fuel lines
  - Some particles still remain

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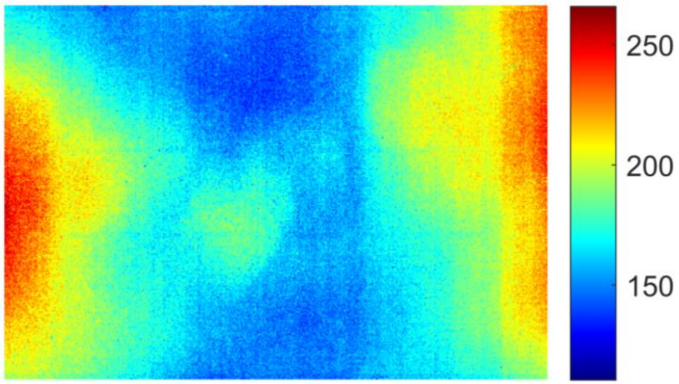
Particle removal and signal recovery

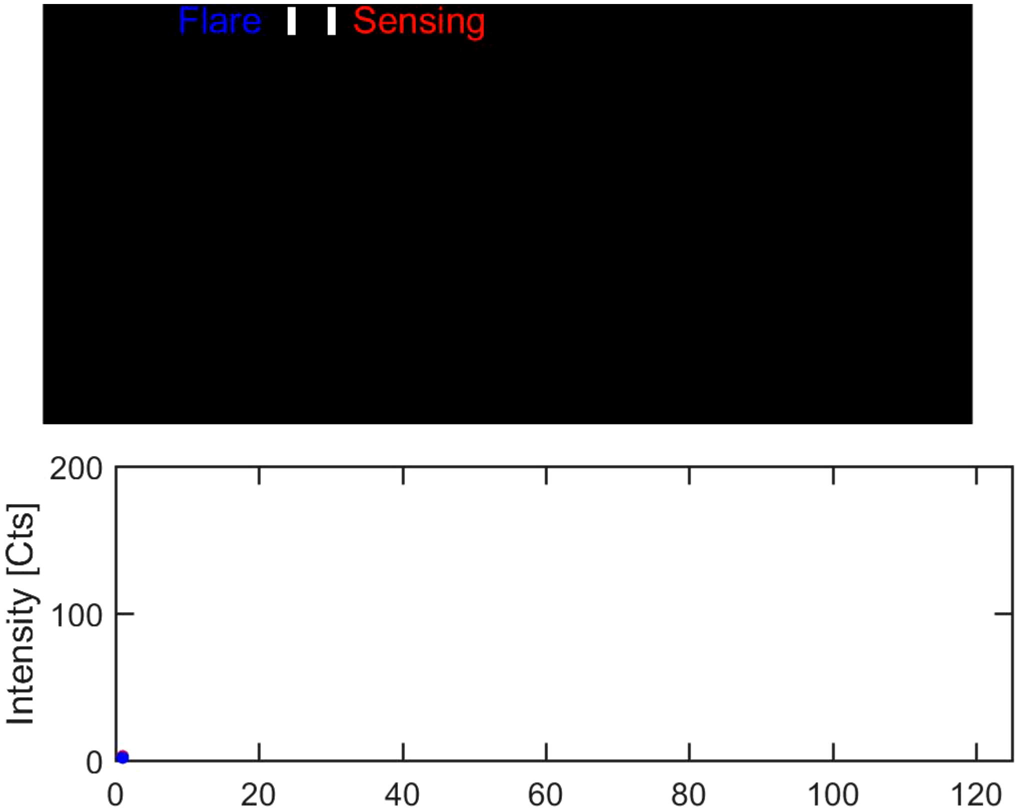
- The high-precision fuel system considerably reduced the amount of particles and/or scatterers
- Image treatment is still necessary to eliminate the remaining particles, which would affect measurement quantities
  - The image processing routine first identifies the particles present on every image
  - Two-dimensional local inpainting is then used to recover the image intensity behind each particle
- No spatial filtering is applied to the image globally
  - But inpainting effectively smoothens the region covered by a particle
  - Most particles being small, the smoothing is spatially limited in practice
- This process has demonstrated to leave the rest of the image unaffected
  - Superior to previously applied method such as spatial filtering and global inpainting

Dynamic flare compensation

- Background flare has a considerable effect on fuel concentration quantification and is laser intensity-dependent
  - Shot-to-shot laser intensity is important and needs to be accounted for
  - Flare needs to be adjusted on a spatial and temporal basis for accurate mixing measurements
- Flare map has been obtained with vessel empty (no pressure)

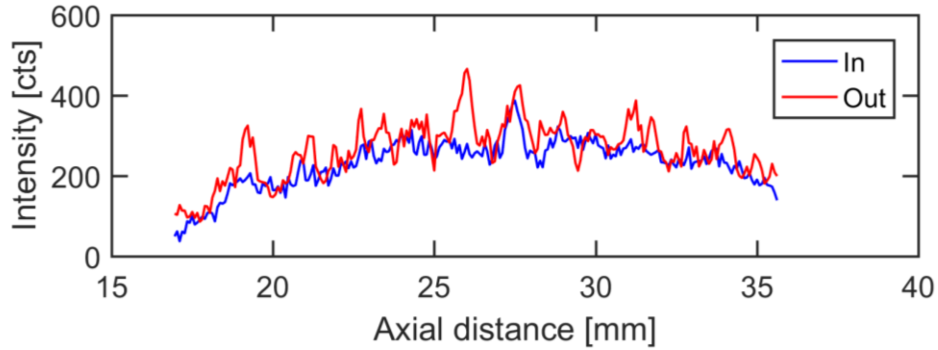


- A sensing region to monitor flare provided the best results
  - 2-D background flare map is adjusted thanks to the sensing region



Spatial laser distribution and beam steering

- Laser intensity varies from shot-to-shot and needs to be quantified
  - Beam steering also affects intensity



- A first method is based on parallel interpolation and corrects laser intensity variations and beam steering simultaneously
  - Detects jet boundary and extract the Rayleigh signal intensity from the ambient on both sides of the jet
  - Parallel interpolation is performed linearly along the laser sheet to produce the ambient reference intensity
- A second approach applies a wavelet filter to reduce beam steering effects on signal intensity
  - Normalizes the signal intensity prior to the jet
  - Wavelet filtering is applied along the laser path to account for intensity variations in the jet region

Mixture and temperature quantification

- Rayleigh scattering can be used to quantify small particles (molecules) such as fuel vapor
  - Proportional to molecule number density and scattering cross-section of a species

$$I = I_0 \cdot \cancel{W} \cdot \cancel{h}_{opt} \cdot \cancel{L}_{opt} \cdot N \cdot \sigma$$

  - The equivalent Rayleigh cross-section of a mixture is proportional to the molar fraction and cross-section of the species

$$\sigma_{mix} = X_{fuel} \times \sigma_{fuel} + X_{amb} \times \sigma_{amb}$$

  - Because the chamber only contains ambient gases and injected fuel: $X_f + X_a = 1$
- The Rayleigh scattered intensity in the ambient is used as reference to self-calibrate the fuel – ambient signal

$$\frac{I_{mix}}{I_{amb}} = \frac{\dfrac{\sigma_{fuel}}{\sigma_{amb}} + \dfrac{N_{amb}}{N_{fuel}}}{\dfrac{N_{amb}}{N_{fuel}} + 1} \frac{T_{amb}}{T_{mix}}$$

- Adiabatic mixing can be applied to assess the temperature of the fuel and ambient mixtures T_{mix} in the jet

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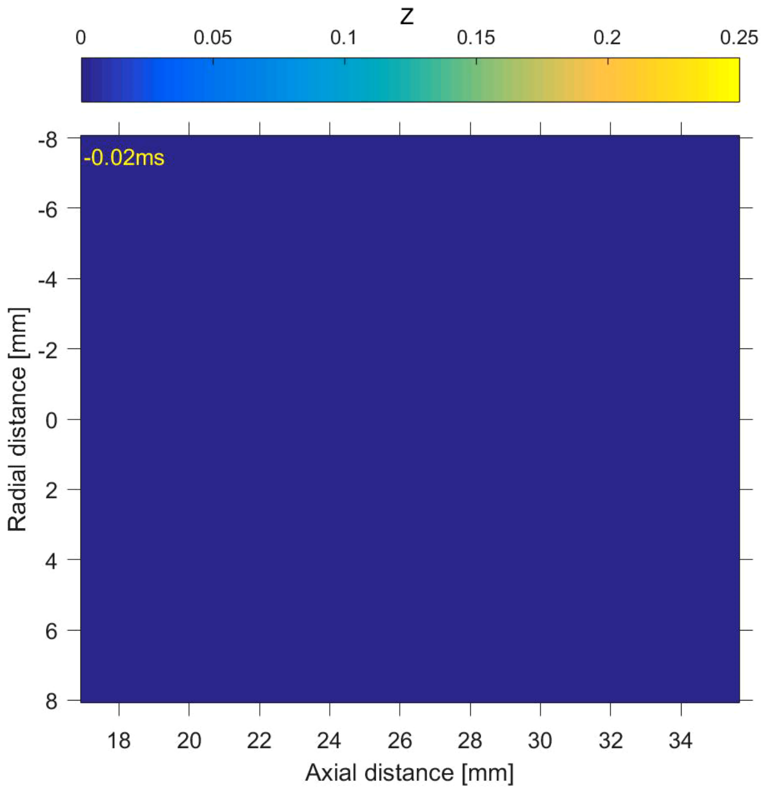
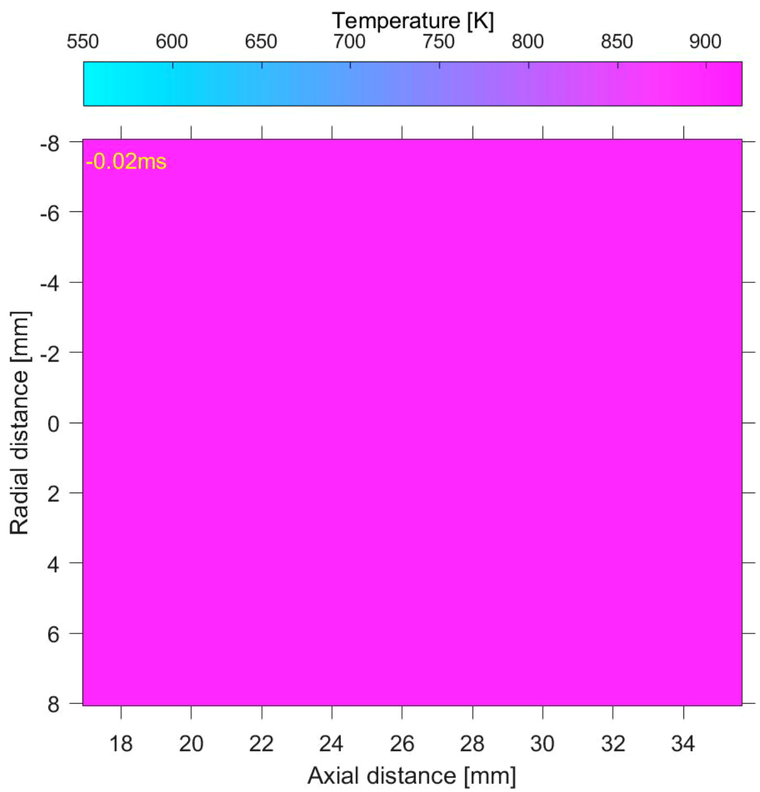
Time-resolved instantaneous fields

- Time resolved 2-D mixture fraction maps for Spray A
  - Highlight the turbulent nature of the mixing process in diesel jets
  - Jet progression shows large structures re-entrainment

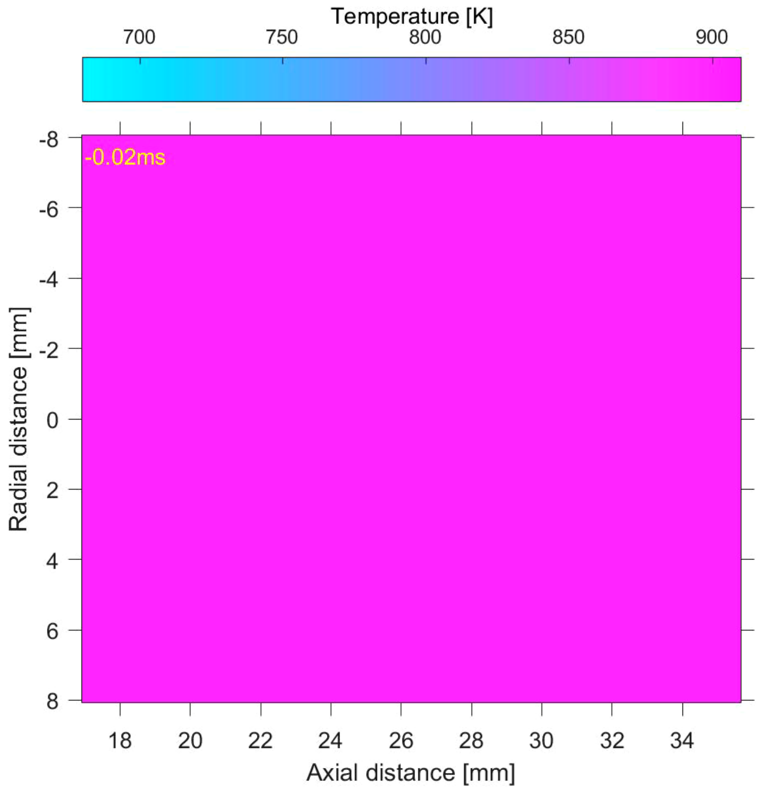


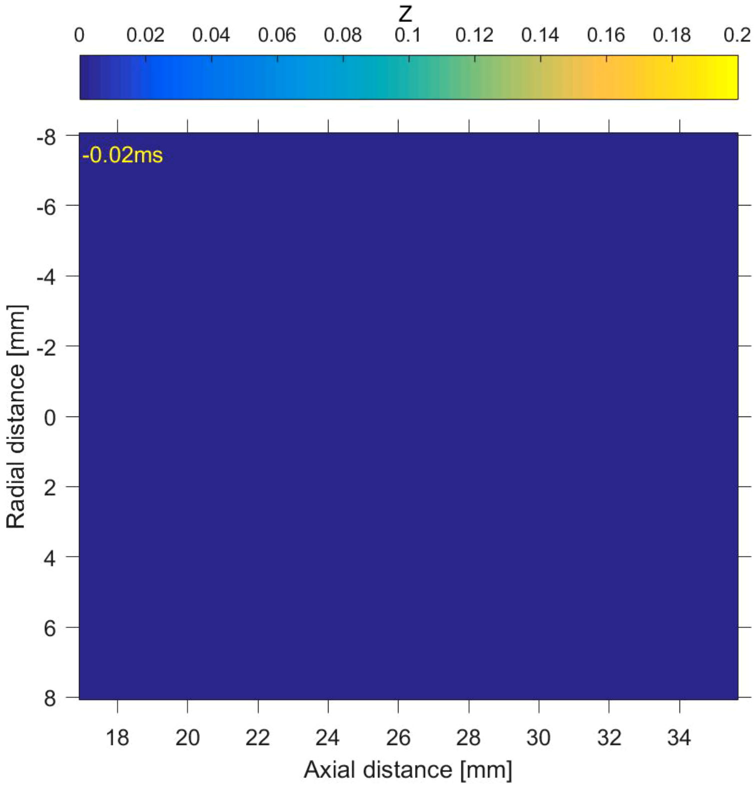


- Adiabatic temperature maps provides information regarding the temperature of the mixture
  - Along with mixing parameters, temperature is important to determine autoignition
  - Relevant for thermodynamic state (transcritical)

Average mixture and temperature fields

- Time-resolved fields averaged over 10 repetitions
  - Detailed mixing features no longer observed
  - Mixing distribution seems location-dependent more than transient

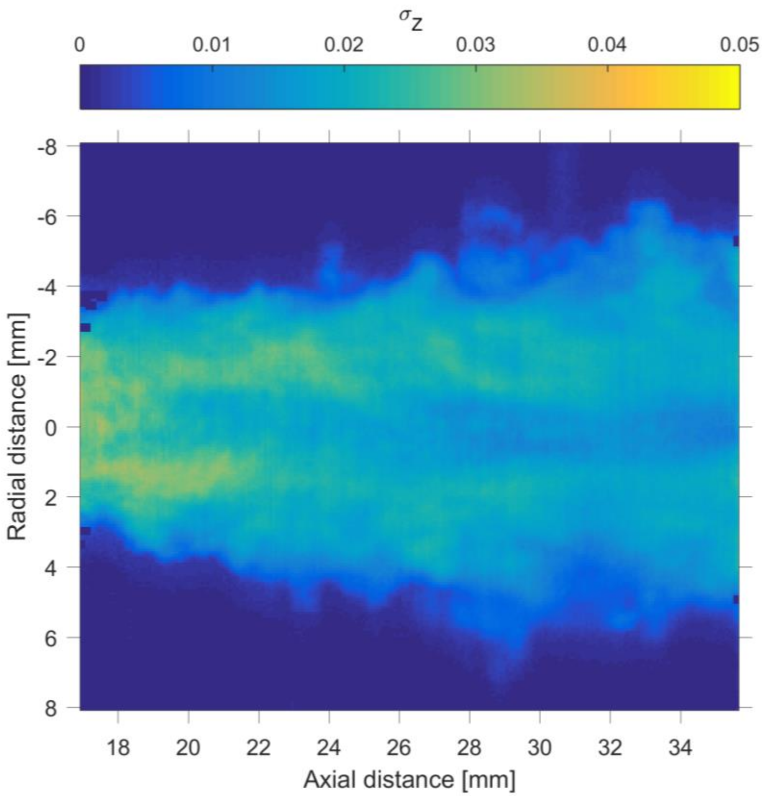


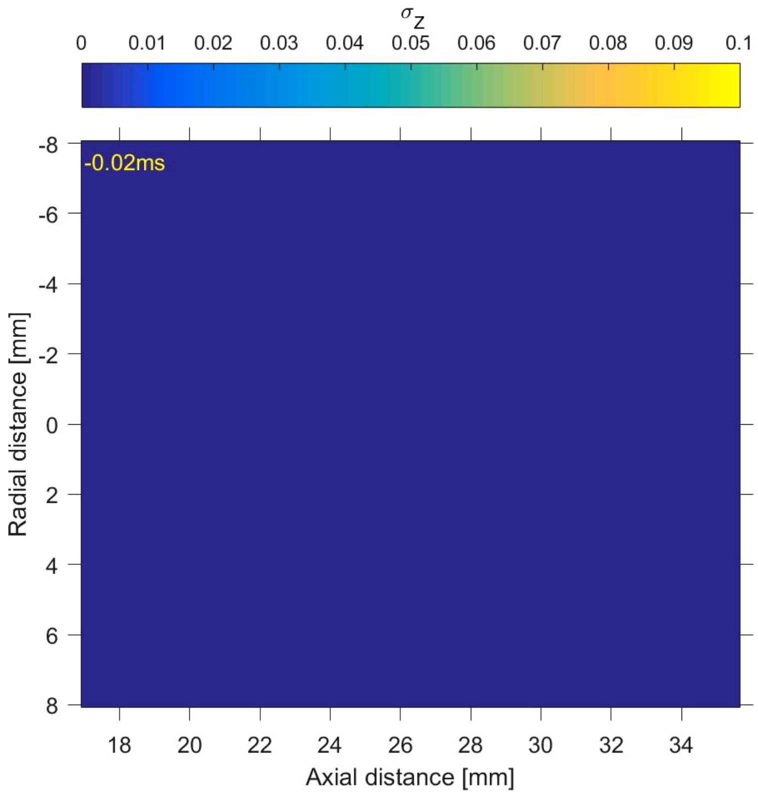


- Mean mixing fields are useful for comparison to models, especially RANS
  - Averaged fields previously required weeks of experiments
  - More repetitions are necessary to reduce statistical variation between injections

Mixing variability

- Time-dependent standard deviation across repetitions shows high variability
  - Jackknife resampling used to enhance statistical confidence
  - Combination of repetition repeatability and jet turbulence

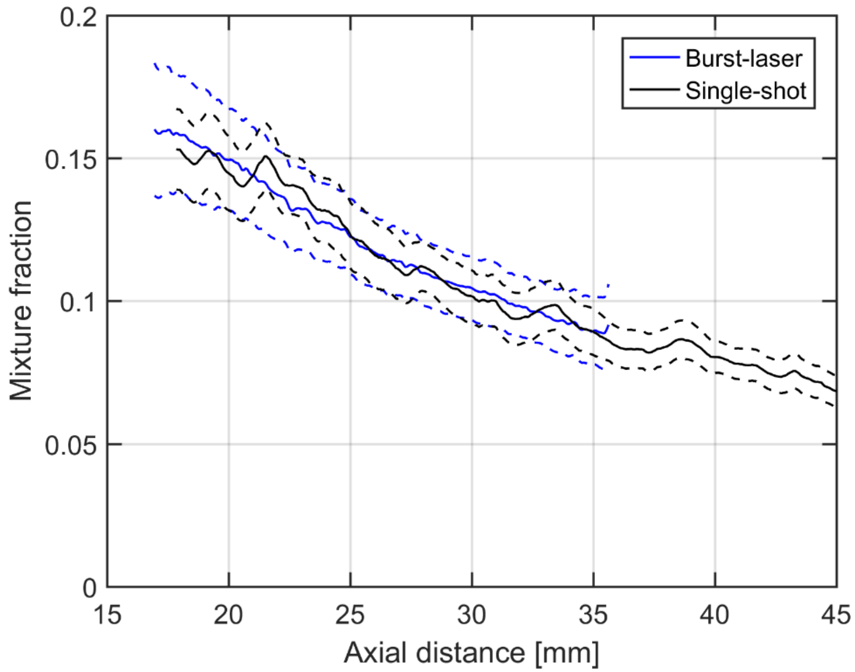


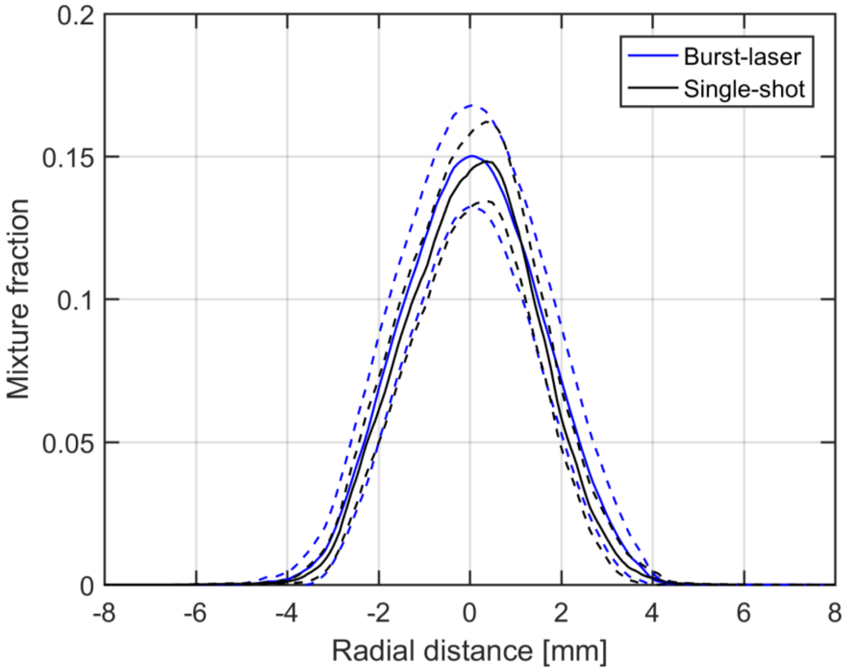


- Standard deviation over quasi-steady period is lower for a single injection
  - Variability should be compared to mean mixture
  - Shows higher relative dispersion on the jet boundaries

Profile comparisons to previous dataset

- Mean mixture fraction axial profile matches that of previous experiments
  - Good agreement between datasets
  - Standard error calculated across repetitions
  - Variations may be expected because of the different injector units used





- Radial profiles also show similar mixing quantities
  - Again, mixture fraction profiles are well within uncertainty for both campaigns
- The good match between datasets provides confidence with the high-speed measurements

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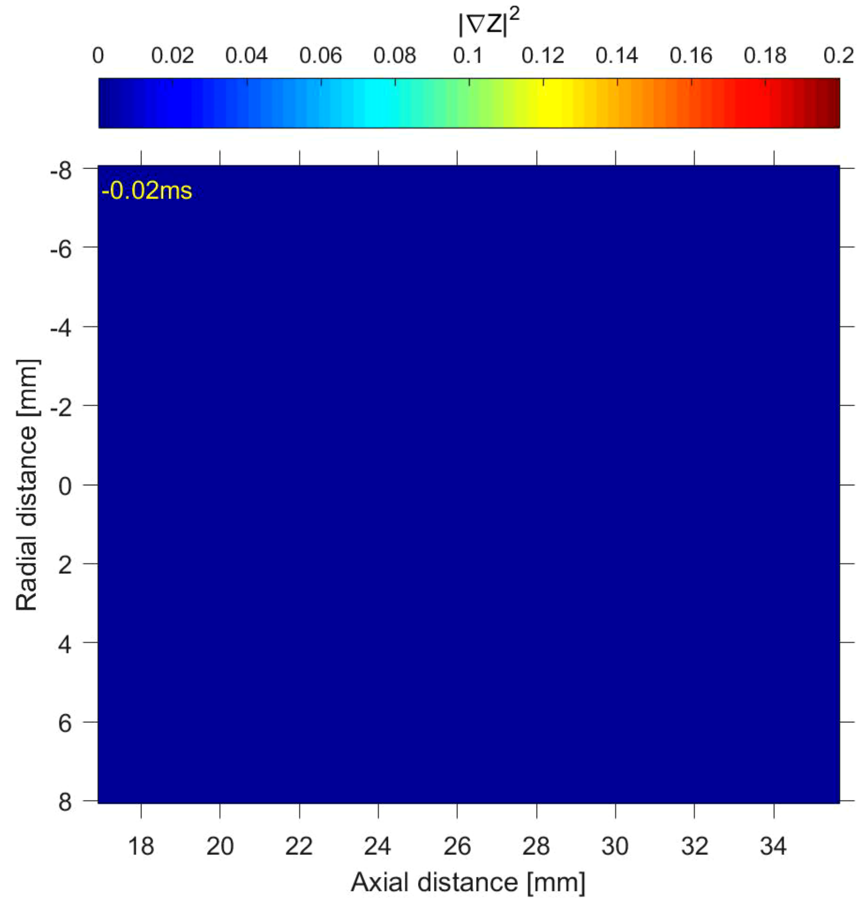
Summary and future work

- Specific equipment has been assembled to allow planar laser Rayleigh scattering imaging measurements in evaporative diesel jets at high-speed
- Advanced image processing methodologies were implemented to mitigate the effects of particle contamination, two-dimensional flare, laser intensity variation and beam steering
- Time-resolved mixing and temperature measurements are available for Spray A
  - Ensemble and temporal average data
  - Mixing variability
  - Time-resolved results compare well with previous dataset
- Detailed mixing quantities are ready for comparisons to high-fidelity CFD simulations
  - Scalar dissipation rate
  - Turbulent length scale
  - Dissipative structure orientation



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Thank you for your attention

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