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Optical diagnostic techniques for spray systems

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Workshop: Utilisation and valorisation of CO₂ for green chemistry
Chemical reactor, Optic methods and Catalyst
19th and 20th February 2015
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Bâtiment Dumont d'Urville, amphi DU BRJ 02
Contents

- Spray systems and spray technology
- Data needed to develop a spray system
- Common optical diagnostic techniques
- Hardware/components to study spray characteristics
- Digital image processing (introduction into typical problems)
- Conclusions
Spray systems and spray technology

Internal combustion engines

Vessels cleaning systems

Water mist fire protection systems

Jet engines/gas turbines

Agriculture

Other

- Food industry
  - Vitamin spraying
  - Product moisturizing
  - Spraying of sugar solutions

- Disinfection
  - Hygiene applications

Picture: http://www.climatetechwiki.org/

Picture: http://chemacinc.com

Picture: http://www.enggencyclopedia.com/

Picture: https://www.asme.org

Picture: http://www.growthproducts.com/
Data needed to develop a spray system

Droplet shape (volume, surface)

Injection nozzle

in-nozzle flow

Tip penetration

Drop size distribution

Spray geometries

primary breakup

secondary breakup

Liquid core

Drop velocity distribution
Common optical diagnostic techniques

- Particle image velocimetry (velocity)
- Schlieren imaging

- High-speed video imaging (size and velocity)
- Direct imaging (size and velocity)
- Phase Doppler anemometry (size and velocity)
- Interferometric laser imaging for droplet sizing (size and velocity)
- Microscopic Imaging (size and velocity)
- Rainbow thermometry (size and temperature)
- Planar laser-induced fluorescence (size and velocity)

(Note: Some techniques are not covered in this presentation.)
**Schlieren imaging**  [Foucault, 1859 and Toepler, 1864]

- Flow visualisation [density gradients]
- Spray visualisation [tip penetration]

Evolution of n-dodecane spray as a function of time after the start of the trigger.
Injection pressure is 1500 bar, ambient is 1 bar

Reflected pressure wave [local speed of sound]
Particle image velocimetry (PIV)

- Flow or droplet velocity can be measured
- Flow must be seeded with small particles or droplets must be present
- Double pulse lasers and double frame cameras are needed

Flow was seeded with Al$_2$O$_3$ particles

PIV image of swirling burning jet

![PIV image of diesel fuel spray [no seeding]](Frame 1) ![Frame 2] Velocity vectors

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Direct imaging

[Dombrowski and Fraser 1954; Chigier, 1976]

• Requirement for high magnification to resolve small droplets
• Spatial resolution issues (high-speed video)

7-hole injector spray

Processed frames

High-speed video of supersonic diesel spray

Mach number = 1.35
Fuel: n-dodecane
Phase Doppler Anemometry (PDA)

[Bachalo & Houser 1984; Saffman et al. 1984; Bauckhage et al. 1987]

- Velocity is computed from Doppler shift (beat frequency)
- Size is computed from the phase difference between two detectors
- Three detectors provide greater resolution and a large measurable size range

- Spherical shapes only
- Particles density limit
- At a point only

Why 2 beams?

\[ \Delta f = \frac{\nu}{c} = 100\% \cdot \frac{10}{299700000} = 3.3367 \times 10^{-6} \]
Interferometric Laser Imaging for Droplet Sizing (ILIDS)

- 2D spatial droplets distribution
- Instantaneous size and velocity (two cameras or a single double frame)

- Spherical droplets only
- Fundamental limit of geometrical optics
- Minimum droplet diameter $2 \times k$
- Maximum droplet diameter $N_{\text{max}} = L/4$

[Golombok et al., 1998]

$$d = N \cdot k$$

$N$ - Fringe count
$k$ – Diameter per fringe

conventional ILIDS technique [Glover et al. 1995]
Interferometric Laser Imaging for Droplet Sizing (ILIDS)

Schematic of the optical configuration of ILIDS including the optical compression unit introduced by Maeda et al., 2000

- Optical compression unit is used to prevent droplets overlapping on screen

S. Sahu, Experimental Study of Isothermal and Evaporative Sprays (PhD thesis), Imperial College London, 2011.
Microscopic Imaging

[Crua et al. 2010; Bae et al. 2002; Badock et al. 1999; Sjöberg et al. 1996]

- High spatial resolution (d<10 µm)
- Spherical and non-spherical droplets including partially formed (ligaments) can be measured
- Velocity of individual droplets can be estimated

- Difficulty with lighting at microscopic level
- Diffraction limit [fundamental limit]

\[
\text{Limit of resolution} = \frac{0.61\lambda}{NA}
\]

colour of light used to illuminate

numerical aperture
Microscopic Imaging (cont.)

7-hole DFI-1.3 injector; nozzle diameter of 135 µm

Shadowgraphs of diesel sprays with sub-micron resolution
Injection at 40 MPa into atmospheric conditions.

- Small droplets are visible
- Initial jet structure is visible
- Detailed spray structure is scanned

Crua et al., ICLASS 2012, Heidelberg, Germany, September 2-6, 2012
Microscopic Imaging (cont.)

Shadowgraphs of diesel sprays with sub-micron resolution
Injection at 100 MPa into high pressure and temperature environment

- Spherical and nearly spherical droplets
- Highly deformed structures [shown in green]
Microscopic Imaging (cont.)

- When microscopic imaging is considered?
  - Initial stage of jet formation
  - Primary breakup
  - Near nozzle effects, e.g. thermal boundary layer

- Diffraction issues (low resolution)
- Significant rejection rate (out of focus) during engine tests

Ambient 1 bar, Injection 500 bar, n-dodecane

Ambient 40 bar, Injection 500 bar, n-dodecane
Hardware/components to study spray characteristics

Constant volume chamber [P<350 bar]

Rapid compression machine [P<120 bar]

- Bore: 135 mm
- Stroke: 150 mm
- Displacement: 2.2 l
- RPM: 500
- T = 540-850 K

Atmospheric chamber [P=1 bar]
Hardware/components to study spray characteristics

- Long-distance microscopes
- Lenses
- Pulsed diode laser light source

High-speed cameras

Low-speed cameras

LED pulsing systems


Picture: http://www.visionresearch.com/Products/High-Speed-Cameras/v710/

Picture: http://www.photonics.com/

Picture: http://www.ila.de/piv/piv-systems/lps.html
Image processing

- There is a need to automatically identify drops in images
- Spherical droplets are relatively easy to account for
- Several optical techniques work well with spherical non-deformed droplets
- Classical approach: Find all pixels, assume sphericity, compute equivalent diameter

Typical questions

- How to get from raw images to binary images?
- What happens if a droplet is not spherical?
- Volume and surface area for deformed droplet?
- Small droplets (pixilation)?
- Measured droplet size/real size?
Conclusions

Key elements in selection of optical diagnostic techniques

- Access into a test section
- Signal acquisition and interpretation
- Specific method and conditions are defined by research tasks

- Particle image velocimetry (velocity)
- Schlieren imaging

- High-speed video imaging (size and velocity)
- Direct imaging (size and velocity)
- Phase Doppler anemometry (size and velocity)
- Interferometric laser imaging for droplet sizing (size and velocity)
- Microscopic Imaging (size and velocity)
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