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Optical diagnostic techniques for spray systems

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Workshop: Utilisation and valorisation of CO$_2$ for green chemistry
Chemical reactor, Optic methods and Catalyst
19$^{th}$ and 20$^{th}$ 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

Jet engines/gas turbines

Vessels cleaning systems

Agriculture

Water mist fire protection systems

Other

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

- Disinfection
  - Hygiene applications
Data needed to develop a spray system

Droplet shape (volume, surface)

Injection nozzle

in-nozzle flow

Spray geometries

Tip penetration

Drop size distribution

Drop velocity distribution

primary breakup

secondary breakup

Liquid core
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)

Flow visualisation techniques

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 present
- Double pulse lasers and double frame cameras are needed
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

High-speed video of diesel spray
[1500 bar into 48 bar ambient]
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?

\[ \Delta f_{\%} = \frac{v}{c} = 100 \% \cdot \frac{10}{299700000} = 3.3367 \cdot 10^{-6} \]
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 $N_{\text{max}} = L/4$

conventional ILIDS technique [Glover et al. 1995]

\[ d = N \cdot k \]

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

[Golombok et al., 1998]
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.

Typical compressed ILIDS image

droplet velocity estimation in ILIDS processing

\[ u_s = \frac{\Delta x}{\Delta t}, \quad v_s = \frac{\Delta y}{\Delta t} \]
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

Spray
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
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

![Image segmentation](image)

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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