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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**

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**Bâtiment Dumont d'Urville, amphi DU BRJ 02**

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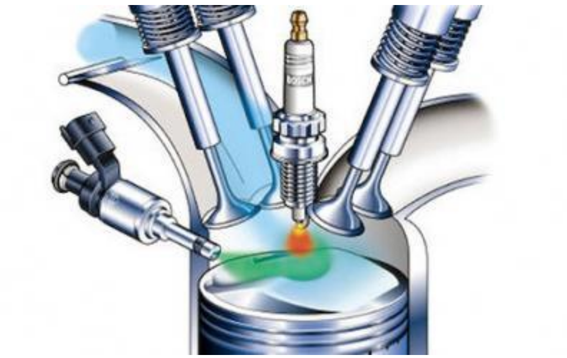
- ❑ Spray systems and spray technology
- ❑ Data needed to develop a spray system
- ❑ Common optical diagnostic techniques
- ❑ Hardware/components to study spray characteristics
- ❑ Digital image processing (introduction into typical problems)
- ❑ Conclusions

# Spray systems and spray technology

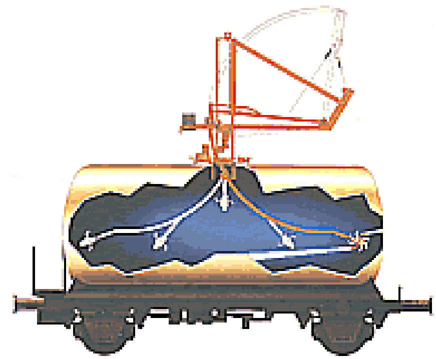


## Internal combustion engines



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

## Vessels cleaning systems

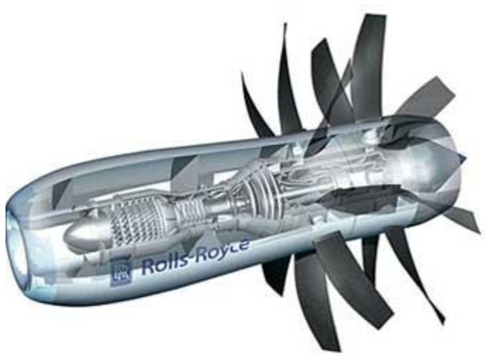


Picture: http://chemacinc.com

## Water mist fire protection systems

Picture: http://www.enggcyclopedia.com/

## Jet engines/gas turbines




Picture: https://www.asme.org

## Agriculture

Picture: http://www.growthproducts.com/

## Other

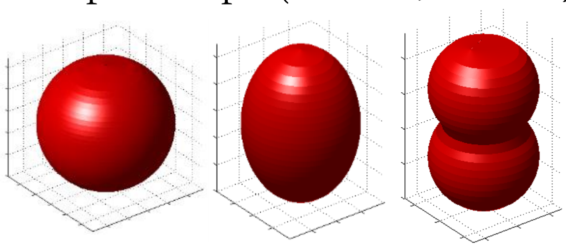
- Food industry
  - Vitamin spraying
  - Product moisturizing
  - Spraying of sugar solutions

- Disinfection
  - Hygiene applications

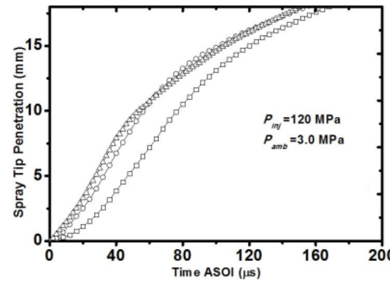
# Data needed to develop a spray system

E3C3 ENERGY EFFICIENCY AND ENVIRONNEMENT CROSS-CHANNEL CLUSTER

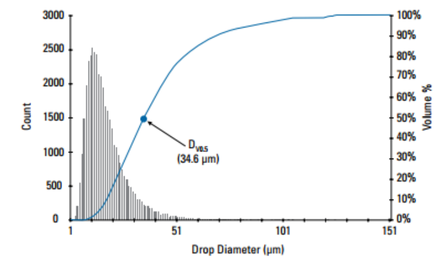
Droplet shape (volume, surface)



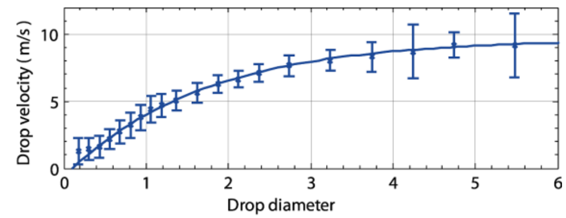
Tip penetration

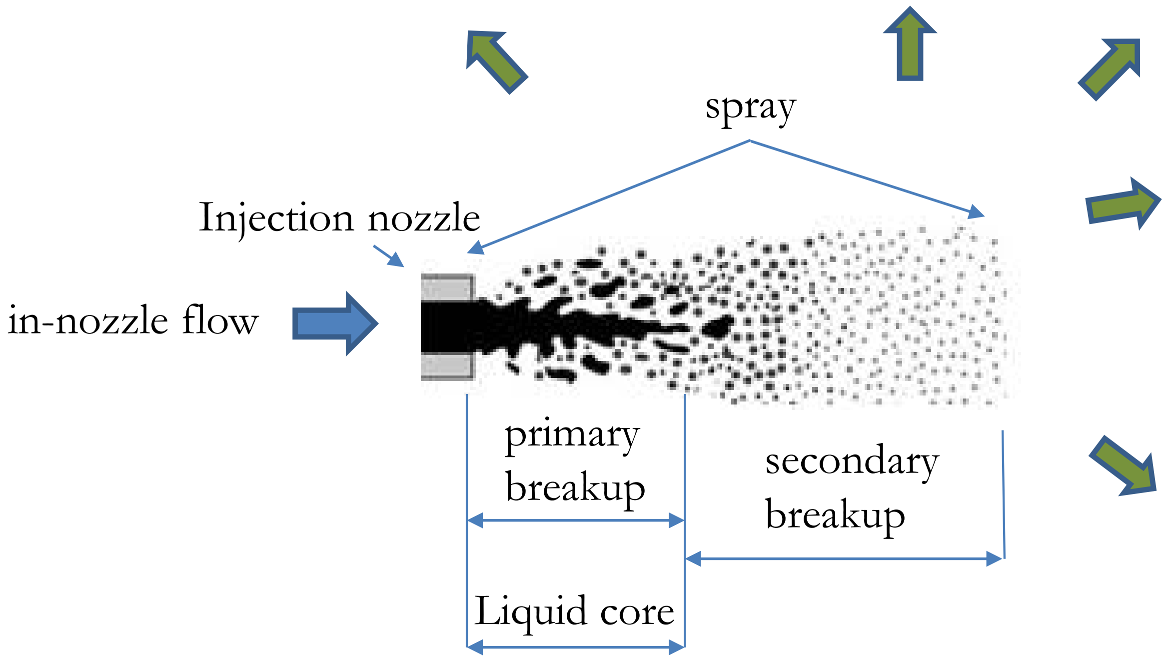



Drop size distribution

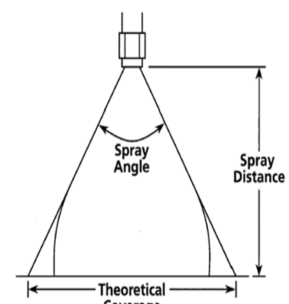



Drop velocity distribution




Spray geometries



# Common optical diagnostic techniques

- Particle image velocimetry (velocity)
- Schlieren imaging

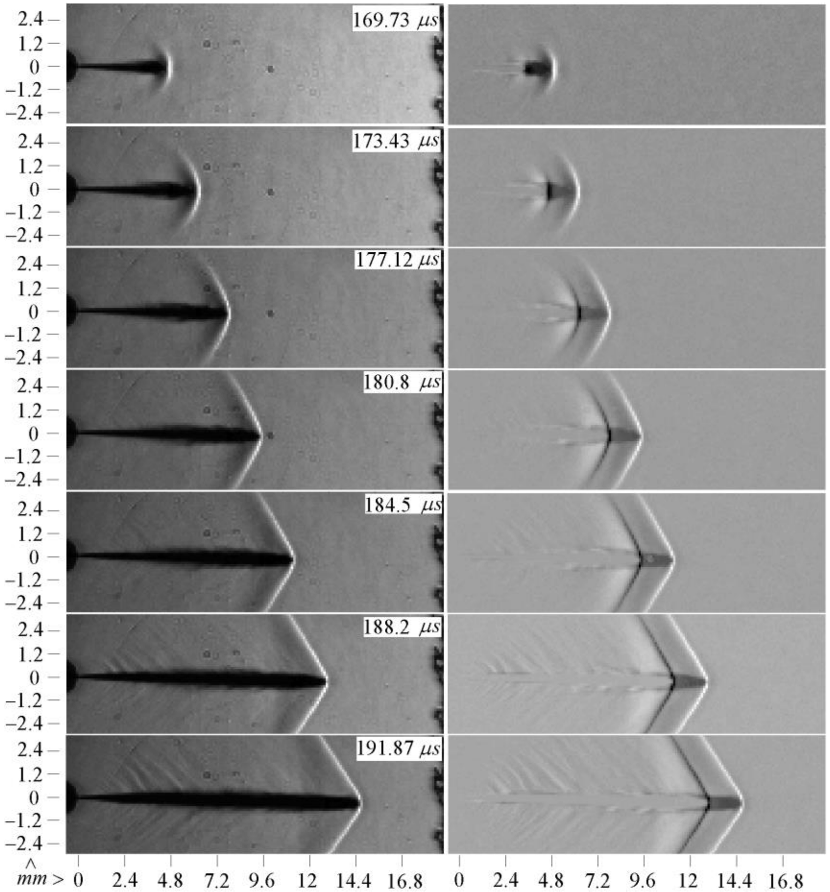
flow visualisation techniques

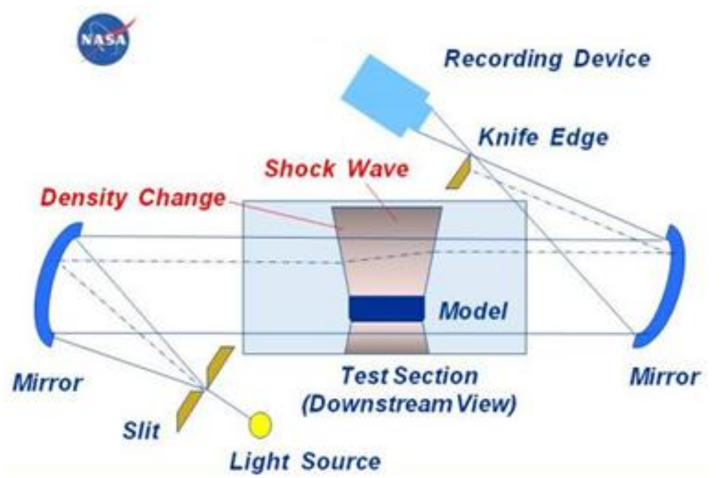
- High-speed video imaging (size and velocity)
- Direct imaging (size and velocity)
- Phase Doppler anemometry (size and velocity)
- Interferometric laser imaging for droplet sizing (size and velocity)
- Microscopic Imaging (size and velocity)
- Rainbow thermometry (size and temperature)
- Planar laser-induced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

not covered in this presentation

# Schlieren imaging [Foucault, 1859 and Toepler, 1864]

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

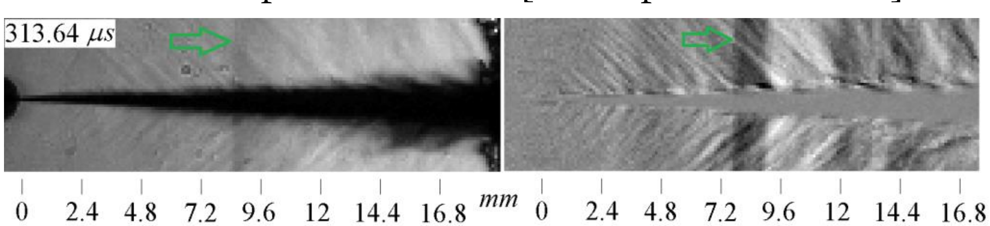



Picture: http://www.grc.nasa.gov/WWW/k-12/airplane/tunvschlrn.html

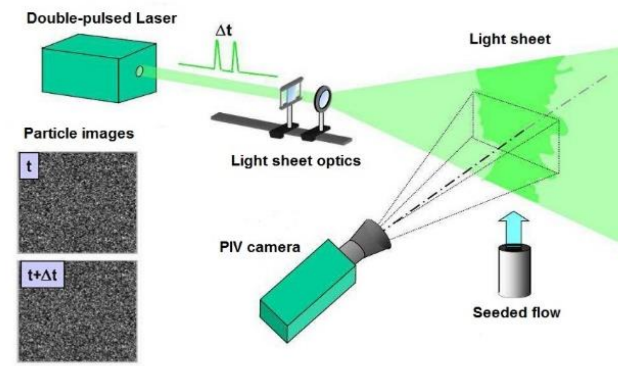
Evolution of n-dodecane spray as a function of time after the start of the trigger.
Injection pressure is 1500 bar, ambient is 1 bar

Reflected pressure wave [local speed of sound]

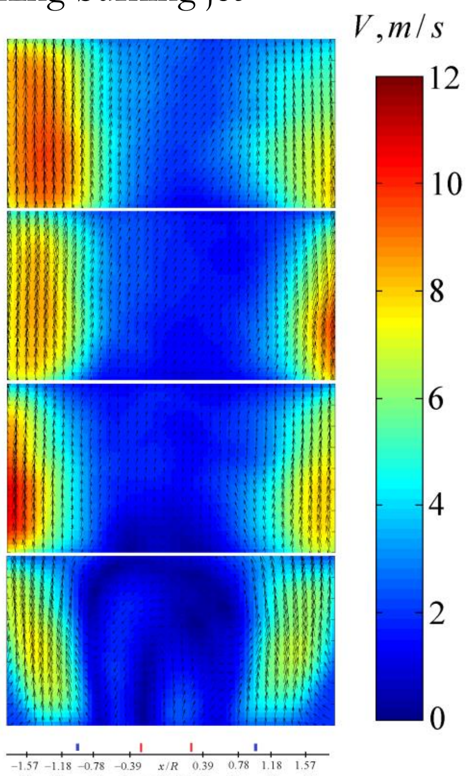


# Particle image velocimetry (PIV)

- 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



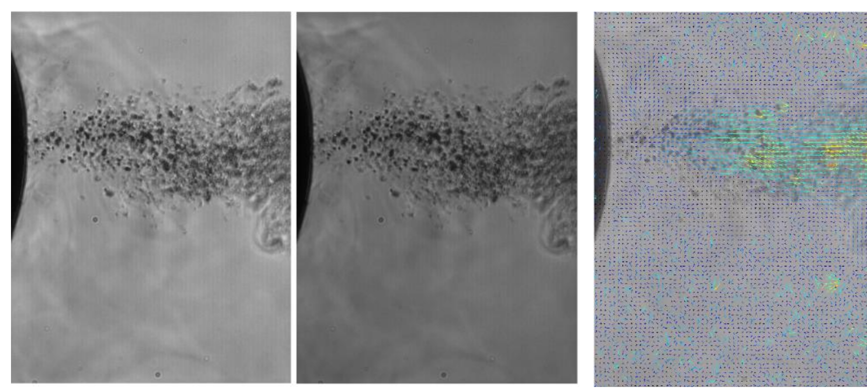

PIV image of swirling burning jet




Flow was seeded with $Al_2O_3$ particles

PIV image of diesel fuel spray [no seeding]

Frame 1 Frame 2 Velocity vectors



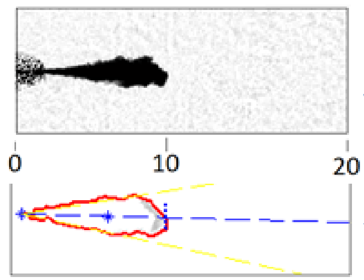
# Direct imaging

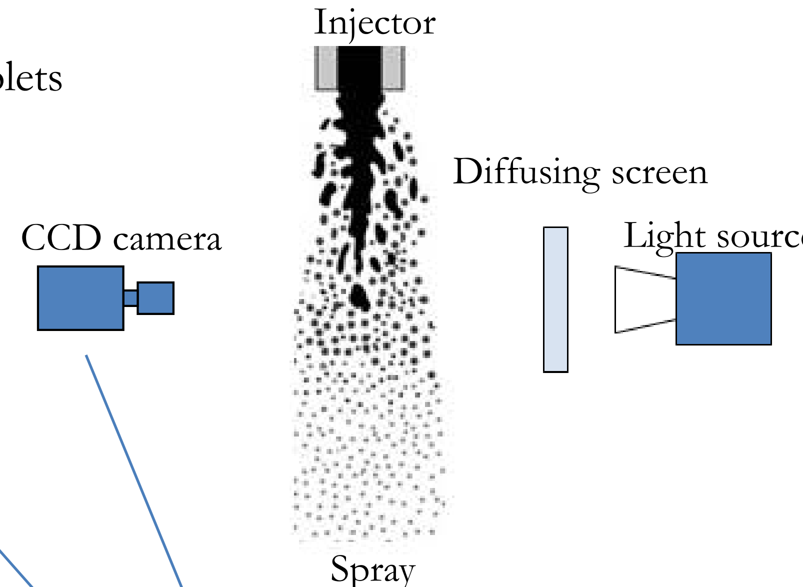
[Dombrowski and Fraser 1954; Chigier, 1976]

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

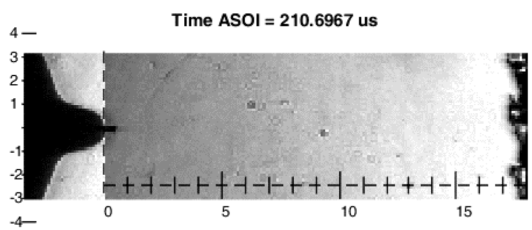
7-hole injector spray

Processed frames



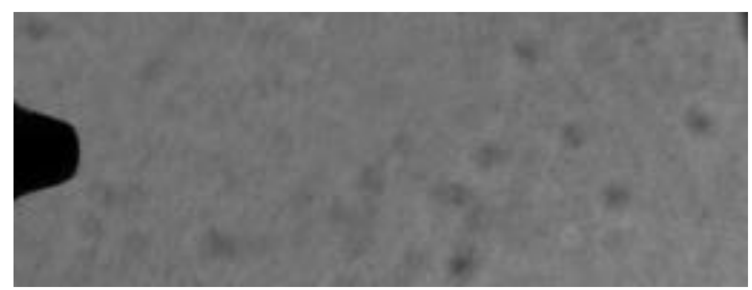




High-speed video
of supersonic diesel spray




Mach number = 1.35
Fuel: n-dodecane

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

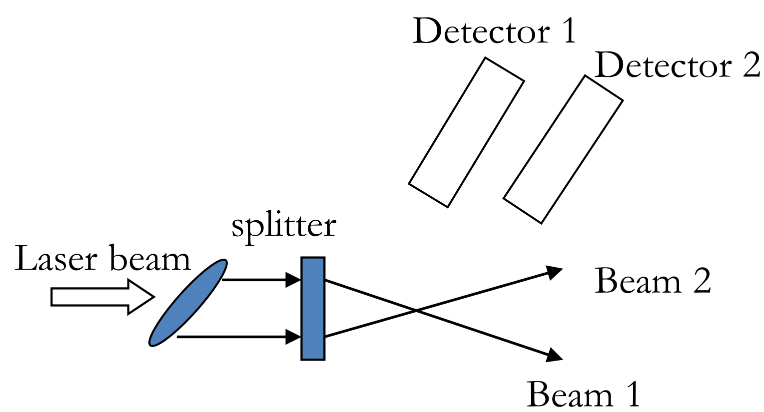


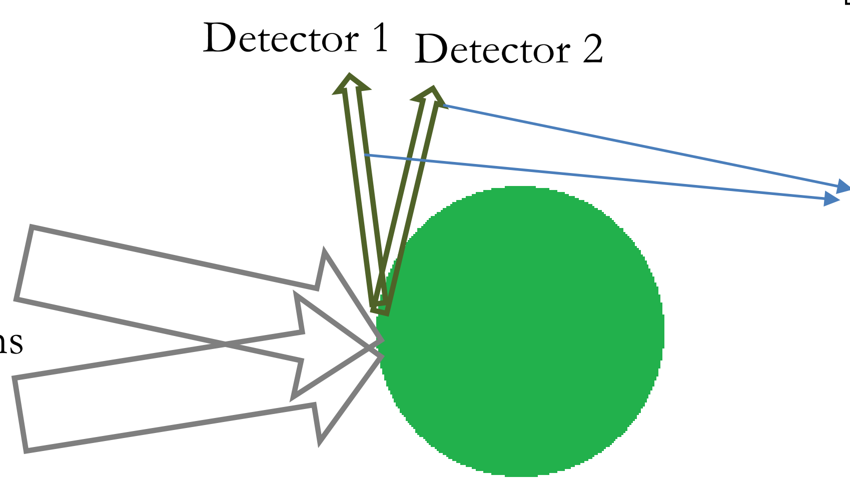
# Phase Doppler Anemometry (PDA)

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

- ❑ Velocity is computed form 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




scattered waves interfere in space and create a beat signal with a frequency which is proportional to the velocity of the particle

Why 2 beams? $\Delta f_{\%} = v/c = 100\%\cdot 10/299700000 = 3.3367e\text{-}06$

# Interferometric Laser Imaging for Droplet Sizing (ILIDS)

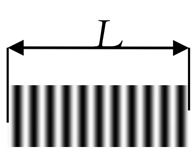
- 2D spatial droplets distribution
- Instantaneous size and velocity (two cameras or a single double frame)

- Spherical droplets only
- Fundamental limit of geometrical optics
- Minimum droplet diameter $2\times k$.
- Maximum droplet diameter Nmax=L/4

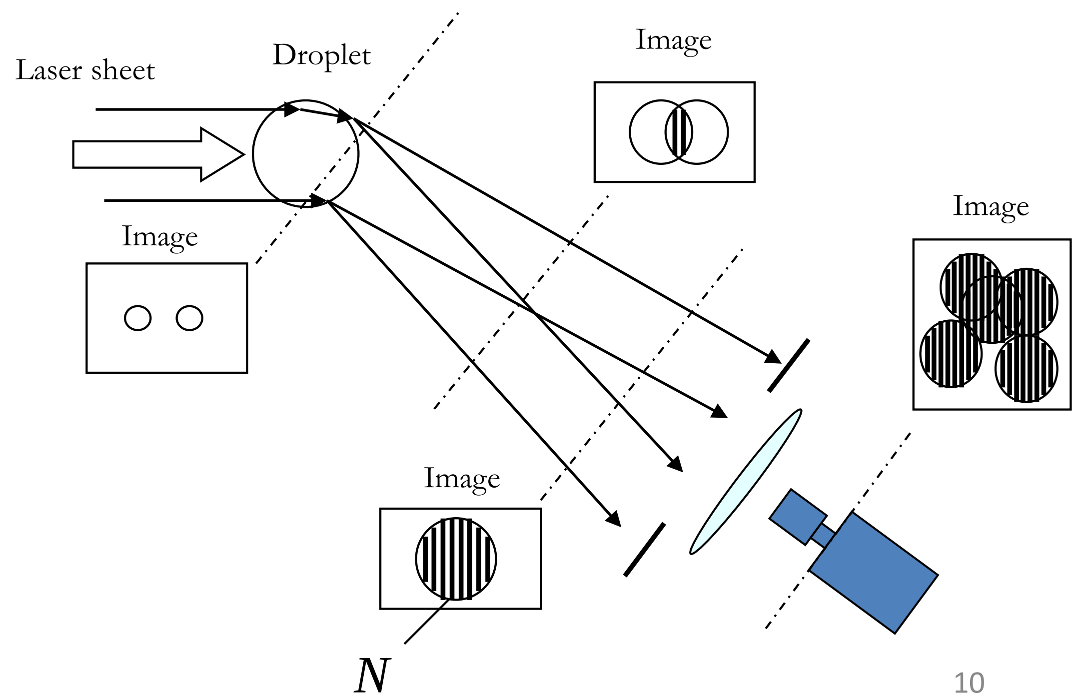
[Golombok *et al.*, 1998]

$$\boxed{d = N \cdot k}$$

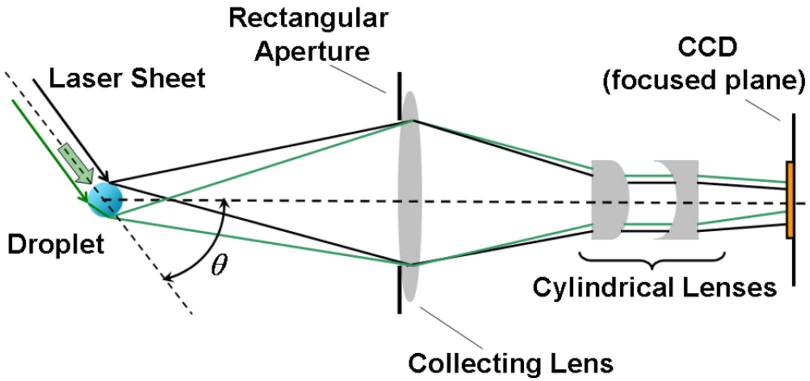
$N$ - Fringe count
$k$ – Diameter per fringe




conventional ILIDS technique [Glover *et al.* 1995]



# Interferometric Laser Imaging for Droplet Sizing (ILIDS)

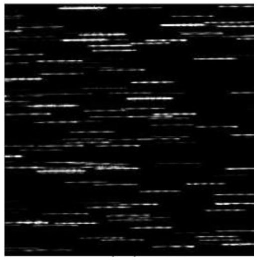



Schematic of the optical configuration of ILIDS including the optical compression unit introduced by Maeda et al., 2000

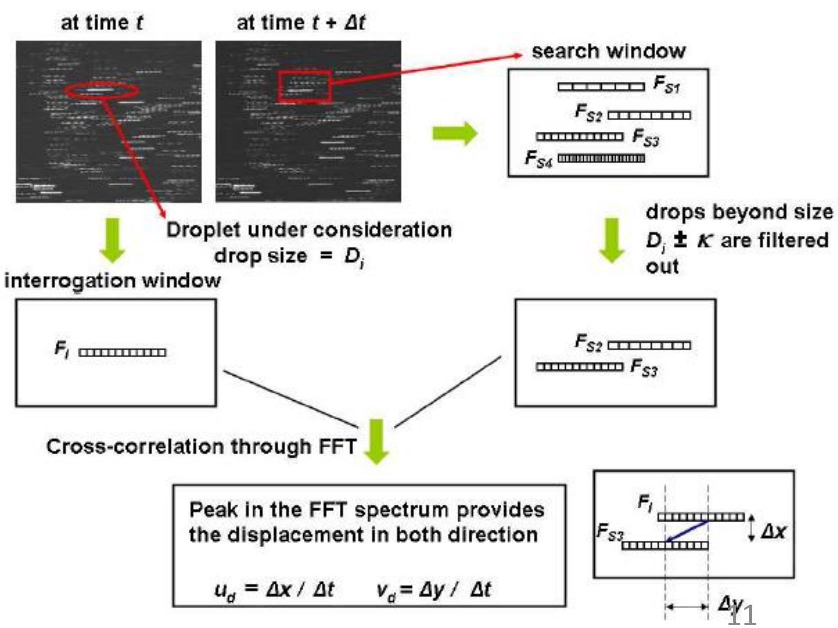
- ❑ Optical compression unit is used to prevent droplets overlapping on screen

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

Typical compressed ILIDS image



droplet velocity estimation in ILIDS processing




University of Brighton

# Microscopic Imaging

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

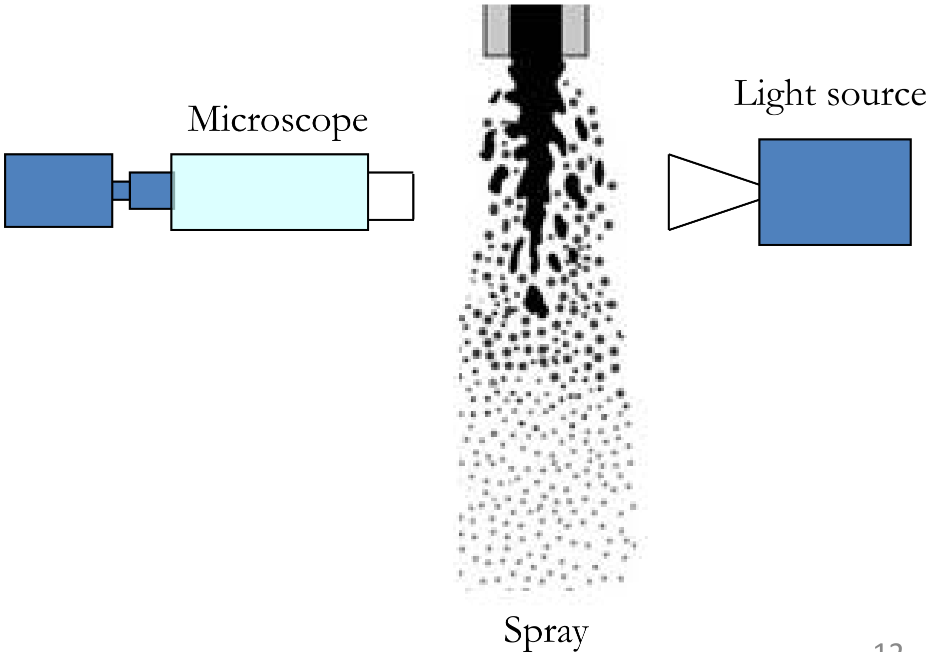
- High spatial resolution (d<10 μm)
- Spherical and non-spherical droplets including partially formed (ligaments) can be measured
- Velocity of individual droplets can be estimated

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

colour of light used to illuminate

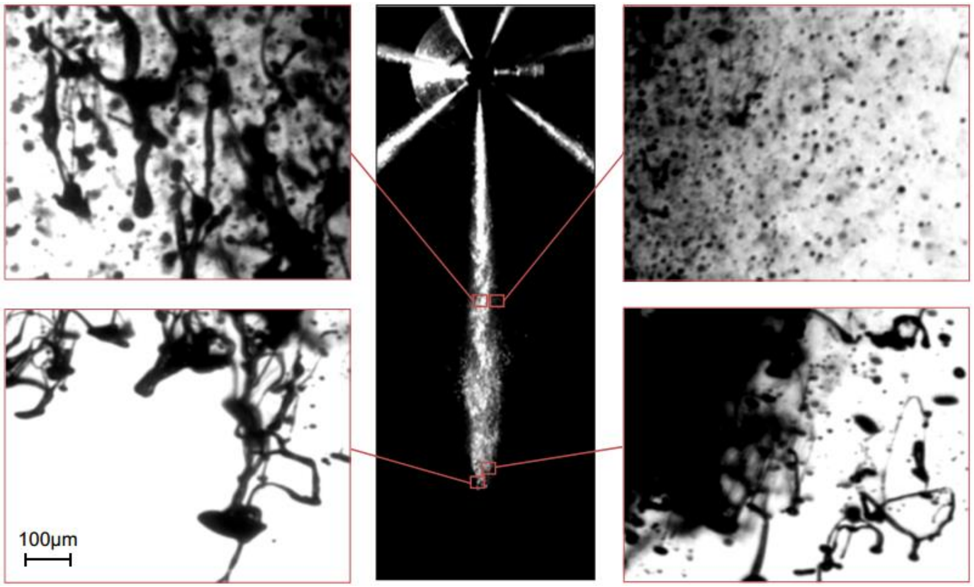
$$\text{Limit of resolution} = \frac{0.61\lambda}{NA}$$

numerical aperture



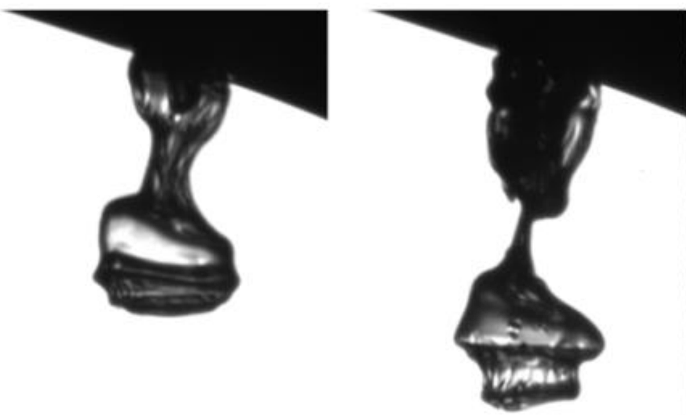
# Microscopic Imaging (cont.)

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

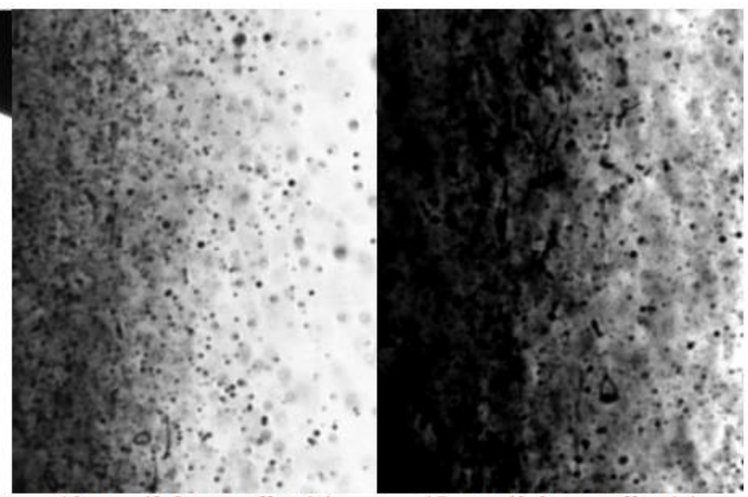



Shadowgraphs of diesel sprays
with sub-micron resolution
Injection at 40 MPa into atmospheric conditions.

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



Dual frame at nozzle exit (dt = 400 ns)

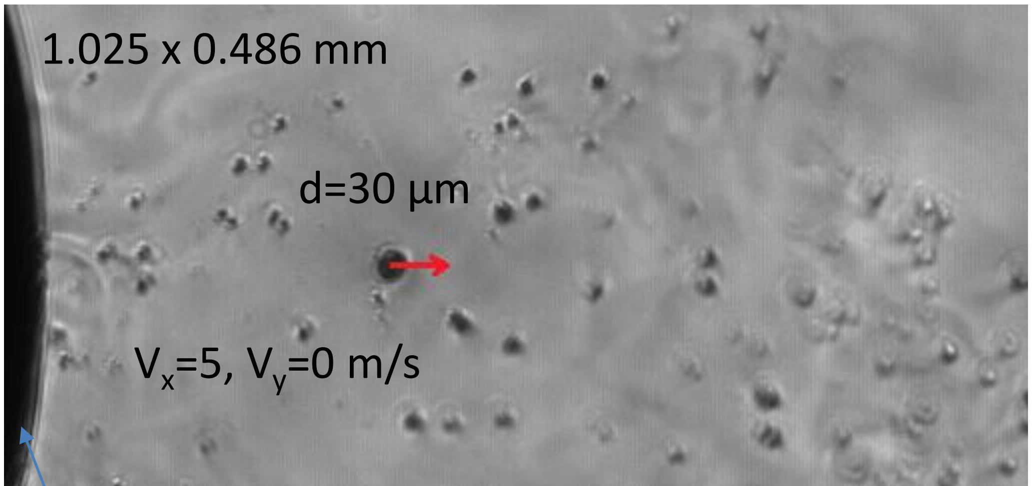


10 mm (0.3 mm off-axis) 15 mm (0.3 mm off-axis)

Crua et al., ICLASS 2012,
Heidelberg, Germany,
September 2-6, 2012

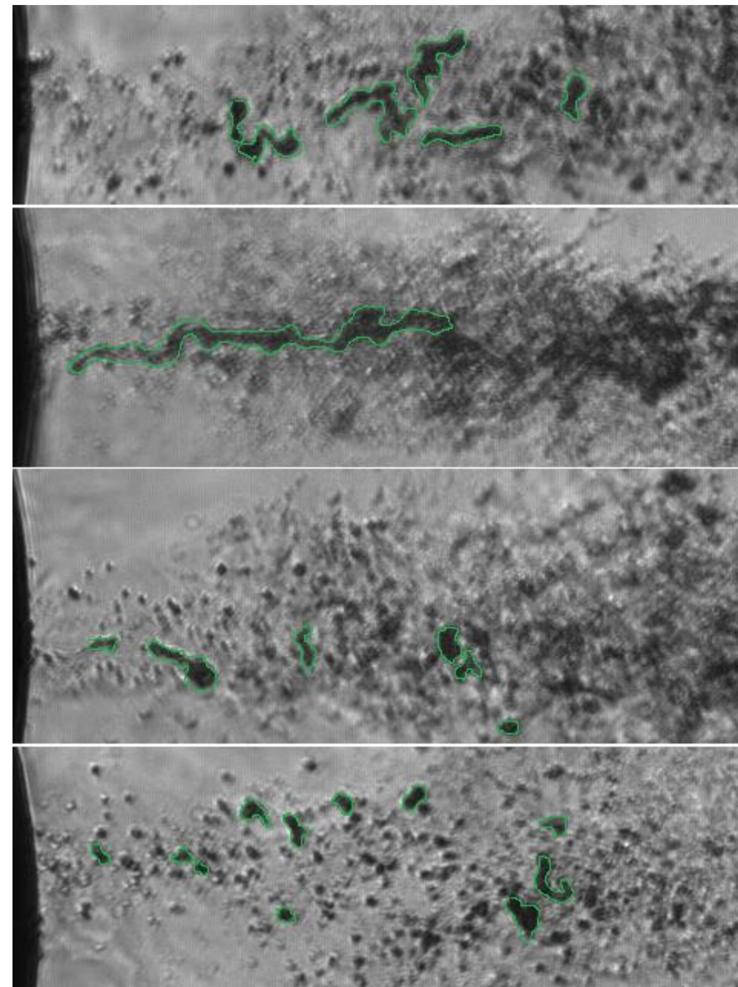
# Microscopic Imaging (cont.)

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




Tip of injector

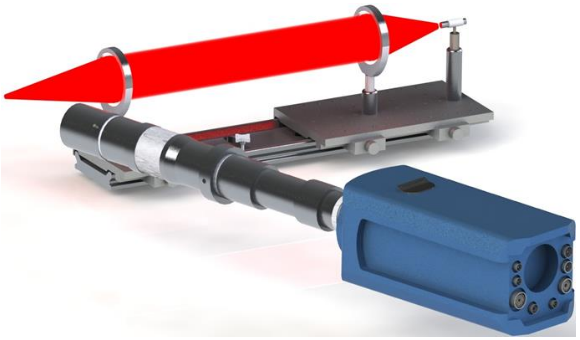
Injection direction



- Spherical and nearly spherical droplets
- Highly deformed structures [shown in green]

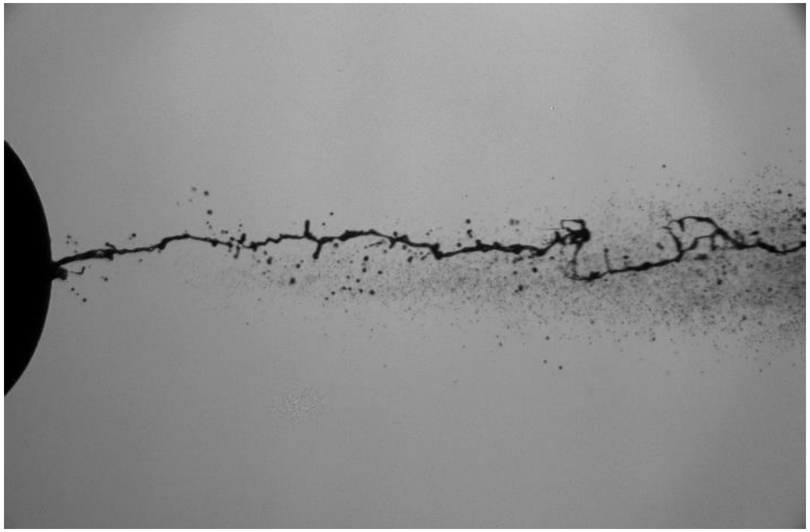
# Microscopic Imaging (cont.)

- 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

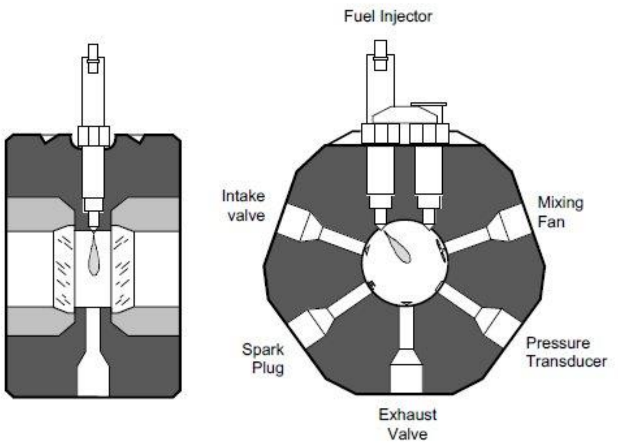
Ambient 1 bar, Injection 500 bar, n-dodecane



Ambient 40 bar, Injection 500 bar, n-dodecane

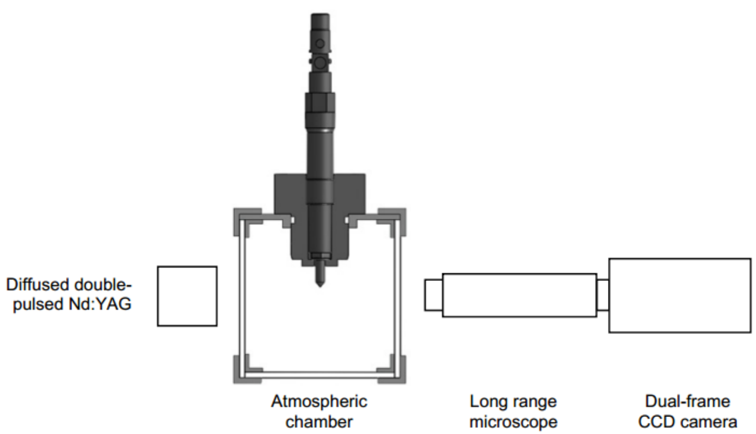
# Hardware/components to study spray characteristics

## Constant volume chamber [P<350 bar]

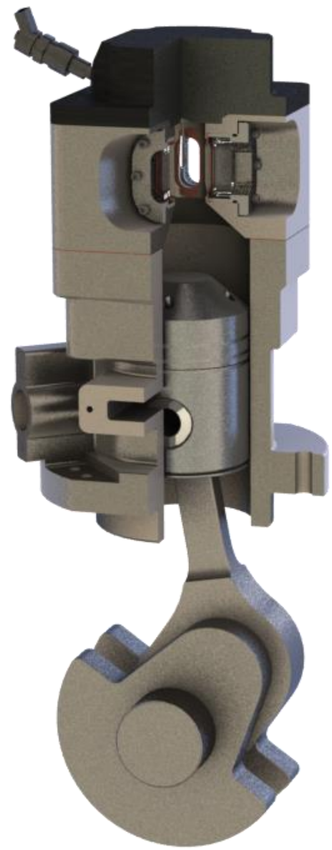



Picture: http://www.sandia.gov/ecn/cvdata/sandiaCV/vesselGeometry-pc.php

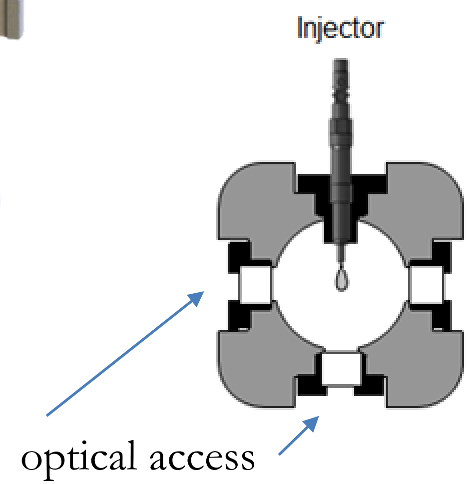
## Atmospheric chamber [P=1 bar]




## Rapid compression machine [P<120 bar]



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



# Hardware/components to study spray characteristics

Long-distance microscopes

Lenses

Pulsed diode laser light source


Picture: https://www.infinity-usa.com/products/instruments/K-Series.aspx

High-speed cameras

Low-speed cameras


LED pulsing systems

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

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

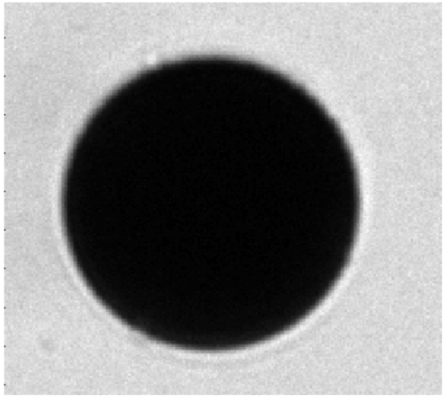
Picture: http://www.ila.de/piv/piv-systems/lps.html

# Image processing

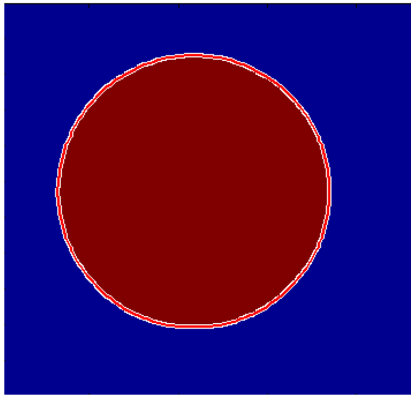
- There is a need to automatically identify drops in images
- Spherical droplets are relatively easy to account for
- Several optical techniques work well with spherical non-deformed droplets
- Classical approach: Find all pixels, assume sphericity, compute equivalent diameter

image segmentation

Raw image



Binary 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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