Spray Characterization

An Overview

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Outline

- Spray Characterization Methods
- Sample Results
- Quality assurance using optical patternator
Aerosol Characterization Techniques

- Light scattering interferometry
- Fraunhofer diffraction
- Laser sheet imaging
- Extinction tomography
- Imaging velocimetry
Light Scattering Interferometry

- Fringe pattern from 2 laser beams
- Particle scatters light and projects pattern
- Detector at one angle provides velocity
- Multiple detectors provide size
### Measurement Characteristics

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol limitations</td>
<td>Spherical, transparent/opaque</td>
</tr>
<tr>
<td>Distance to sample</td>
<td>&lt; 3m</td>
</tr>
<tr>
<td>Probe volume</td>
<td>small</td>
</tr>
<tr>
<td>Size</td>
<td>1-500μm</td>
</tr>
<tr>
<td>Number limitation</td>
<td>Coincident, extinction</td>
</tr>
<tr>
<td>Sampling type</td>
<td>Flux dependent</td>
</tr>
<tr>
<td>Measured quantities</td>
<td>Velocity, size</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>50</td>
</tr>
<tr>
<td>Sampling mode</td>
<td>Time averaged, time resolved</td>
</tr>
<tr>
<td>Sensitivity highest</td>
<td>large drops</td>
</tr>
</tbody>
</table>
Fraunhofer Diffraction

- Scattered intensity from laser beam
- Array detectors measures intensity at different angles
- Mie scattering theory for particle size
### Measurement Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerosol limitations</strong></td>
<td>None on shape/better if opaque</td>
</tr>
<tr>
<td><strong>Distance to sample</strong></td>
<td>&lt; 0.5 m</td>
</tr>
<tr>
<td><strong>Probe volume</strong></td>
<td>Line of sight</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>0.3-500 μm</td>
</tr>
<tr>
<td><strong>Number limitation</strong></td>
<td>Extinction, multiple scattering</td>
</tr>
<tr>
<td><strong>Sampling type</strong></td>
<td>Concentration</td>
</tr>
<tr>
<td><strong>Measured quantities</strong></td>
<td>Size</td>
</tr>
<tr>
<td><strong>Dynamic range</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>Sampling mode</strong></td>
<td>Time averaged, time resolved</td>
</tr>
<tr>
<td><strong>Sensitivity highest</strong></td>
<td>Middle range of drop sizes</td>
</tr>
</tbody>
</table>
Laser Sheet Imaging

- Laser sheet to illuminate spray
- Image taken using a CCD camera at an oblique angle
- Intensity proportional to drop surface area per unit volume

**Potential Errors**

- Laser extinction
- Signal attenuation
- Secondary emission

**Implication:** Qualitative patternation
# Measurement Characteristics

<table>
<thead>
<tr>
<th>Aerosol limitations</th>
<th>Spherical particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to sample</td>
<td>&lt; 0.5 m</td>
</tr>
<tr>
<td>Probe volume</td>
<td>Planar, volume</td>
</tr>
<tr>
<td>Size</td>
<td>3-unlimited</td>
</tr>
<tr>
<td>Number limitation</td>
<td>Extinction, image overlap</td>
</tr>
<tr>
<td>Sampling type</td>
<td>Concentration dependent</td>
</tr>
<tr>
<td>Measured quantities</td>
<td>Light intensity</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>20</td>
</tr>
<tr>
<td>Sampling mode</td>
<td>Instantaneous</td>
</tr>
<tr>
<td>Sensitivity highest</td>
<td>Largest drops</td>
</tr>
</tbody>
</table>
Extinction Tomography (SETscan)

- Turbulent flow
- Laser
- Laser sheet
- Array detector

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Principle of Operation

- Path integrated extinction of laser sheets
- Multiple view angles for non-axisymmetric turbulent flows
- Multiple slices to obtain high spatial resolution
- Local extinction coefficients obtained by statistical tomography (MLE method)
- For liquid sprays, the local extinction coefficients is equal to the drop surface areas per unit volume
### Measurement Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol limitations</td>
<td>Unrestricted</td>
</tr>
<tr>
<td>Distance to sample</td>
<td>Unrestricted</td>
</tr>
<tr>
<td>Probe volume</td>
<td>Planar</td>
</tr>
<tr>
<td>Size</td>
<td>Unrestricted</td>
</tr>
<tr>
<td>Number limitation</td>
<td>Extinction</td>
</tr>
<tr>
<td>Sampling type</td>
<td>Concentration</td>
</tr>
<tr>
<td>Measured quantities</td>
<td>Surface area * no. of drops/m³</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>Instrument SNR</td>
</tr>
<tr>
<td>Sampling mode</td>
<td>Instantaneous, time averaged, time resolved</td>
</tr>
<tr>
<td>Sensitivity highest</td>
<td>Uniform across range</td>
</tr>
</tbody>
</table>
Why surface area density

- Total amount of fuel or liquid evaporated is proportional to heat release rate in combustion and solid mass fraction in spray drying.
- Correlation coefficient (R) of different parameters with total fuel evaporated:
  - Mass flux $R = 0.903$
  - Velocity $R = -0.239$
  - Diameter $= 0.681$
  - Surface area density $= 0.961$

For combustion, spray drying, and urea dosing applications, surface area density is optimal method of comparing different nozzles or checking uniformity.
Comparison with Competitive Technology

- Extinction ⇒ Immune to environmental lighting
- Diode lasers ⇒ Class II, No safety issues
- Monolithic ⇒ Out-of-box factory floor deployment
- Adaptive grids ⇒ Alignment of nozzle not critical
- Advanced GUI ⇒ Easily operated by technician
- Reliable ⇒ 100% quality assurance of nozzles

*Only quantitative (+/- 2% on absolute values, +/- .5% repeatability) patternator on the market*
## Comparison of Methods

<table>
<thead>
<tr>
<th>Measurement Characteristics</th>
<th>Light Scattering Interferometry</th>
<th>Fraunhofer Diffraction, Ensem</th>
<th>Light Sheet Imaging</th>
<th>Extinction Tomography</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Measurement</strong></td>
<td>Diameter/Velocity</td>
<td>Diameter</td>
<td>Pattern</td>
<td>Surface area</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>+/- 20%</td>
<td>+/- 20%</td>
<td>Not quantitative</td>
<td>+/- 2%</td>
</tr>
<tr>
<td><strong>Particle Shape Restriction</strong></td>
<td>Spherical</td>
<td>Sphere, Irregular</td>
<td>Spherical</td>
<td>None</td>
</tr>
<tr>
<td><strong>Particle Composition</strong></td>
<td>Transparent, Opaque</td>
<td>Better if opaque</td>
<td>None</td>
<td>none</td>
</tr>
<tr>
<td><strong>Index of Refraction Dependence</strong></td>
<td>Yes</td>
<td>Partial/none</td>
<td>None</td>
<td>None/Imaginary</td>
</tr>
<tr>
<td><strong>Working distance (Trans to Det)</strong></td>
<td>3 m</td>
<td>0.5 m</td>
<td>0.5m</td>
<td>Unlimited</td>
</tr>
<tr>
<td><strong>Sample Volume</strong></td>
<td>Small, Point</td>
<td>Line of site</td>
<td>Plane/volume</td>
<td>Plane/volume</td>
</tr>
<tr>
<td><strong>Sample Volume Bias</strong></td>
<td>Yes, Correction</td>
<td>None</td>
<td>Yes, Correction</td>
<td>None</td>
</tr>
<tr>
<td><strong>Size Minimum, mm</strong></td>
<td>0.3</td>
<td>0.3</td>
<td>3</td>
<td>Unlimited</td>
</tr>
<tr>
<td><strong>Maximum size</strong></td>
<td>1,000</td>
<td>500</td>
<td>unlimited</td>
<td>Unlimited</td>
</tr>
<tr>
<td><strong>Number Density Maximum</strong></td>
<td>Coincid/extinction</td>
<td>Extinction/MultiScat</td>
<td>Extinction/overlap</td>
<td>Extinction</td>
</tr>
<tr>
<td><strong>Number Density Minimum</strong></td>
<td>None</td>
<td>Yes, Low SNR</td>
<td>Blank Images</td>
<td>Low SNR</td>
</tr>
<tr>
<td><strong>Sampling Type</strong></td>
<td>Flux Dependent</td>
<td>Concentration</td>
<td>Concentration</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Sampling Mode</strong></td>
<td>Time ave/</td>
<td>Instantaneous/</td>
<td>Instantaneous</td>
<td>Time Ave, Time</td>
</tr>
<tr>
<td><strong>Size Dynamic Range</strong></td>
<td>50</td>
<td>50</td>
<td>20</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Particle Velocity</strong></td>
<td>Yes</td>
<td>No</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td><strong>Number Density Measurements</strong></td>
<td>Yes</td>
<td>Yes, With extinction</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Measurement Sensitivity</strong></td>
<td>Highest for largest</td>
<td>Highest for middle</td>
<td>Highest for largest</td>
<td>Uniform across range</td>
</tr>
</tbody>
</table>
Imaging Velocimetry

- Two types for planar information
- Planar Particle Imaging Velocimetry and Statistical Pattern Imaging Velocimetry
- First type tracks individual particles and determines displacement
- Second type tracks flow patterns and determines peak spatial correlations over a fixed time window
Advantages and Disadvantages of SPIV

**Advantages**
- Does not require distinct particles
- Works with various types of lighting such as shadowgraphy and natural lighting
- Work equally well with dense sprays
- High powered lasers not required

**Disadvantages**
- Bimodal velocity difficult to resolve
- Longer computational time required
- Minimum 10 KHz camera
Sample Results

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Sample Results (PDA)

**Radial Position (mm)**

**Y-Velocity (m/s)**

- 40psi, 40gpm
- 40psi, 150gpm
- 70psi, 40gpm
- 70psi, 150gpm
- 70psi, 400gpm
- 100psi, 150gpm
- 100psi, 400gpm

**Radial Position (mm)**

**X-Velocity (m/s)**

- 70psi, 40gpm
- 70psi, 150gpm
- 70psi, 400gpm

**Radial Position (mm)**

**Diameter (microns)**

- 100psi, 4.75% D.C
- 100psi, 23% D.C
- 100psi, 73% D.C

**Radial Position (mm)**

**Diameter (microns)**

- 100psi, 4.75% D.C
- 100psi, 23% D.C
- 100psi, 73% D.C

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Sample Results (Malvern)

- **40 PSI, Malvern Data Test 4**

  - **Characteristic diameters, µm**
  - **Distance, inches**

  - **Single line data**
  - **Two data points at each condition**

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Sample Results Patternator

- Struts signature seen in drop surface area map
- Hollow cone seen as hollow
- Drip from nozzle seen at the center
Automotive Injector

<table>
<thead>
<tr>
<th>Mean plume angles (deg.)</th>
<th>% area in plume</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.89</td>
<td>19.32</td>
</tr>
<tr>
<td>5.73</td>
<td>4.69</td>
</tr>
<tr>
<td>11.53</td>
<td>21.71</td>
</tr>
<tr>
<td>10.48</td>
<td>17.91</td>
</tr>
<tr>
<td>11.51</td>
<td>23.06</td>
</tr>
<tr>
<td>9.35</td>
<td>12.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean centroid (x, mm)</th>
<th>Mean centroid (y, mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.26</td>
<td>-5.69</td>
</tr>
<tr>
<td>-4.84</td>
<td>14.28</td>
</tr>
<tr>
<td>-22.13</td>
<td>1.97</td>
</tr>
<tr>
<td>-29.04</td>
<td>-10.75</td>
</tr>
<tr>
<td>-15.37</td>
<td>-18.49</td>
</tr>
<tr>
<td>0.10</td>
<td>-20.01</td>
</tr>
</tbody>
</table>

Reliable data with multiple orifice injectors

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PDA vs Patternator (Agreement)

Calculated Absorption Contour Plot

Patternators Extinction

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PDA vs Patternator (Discrepancy)

- Agreement (within 20% – 30%) when: Data-rate < 30,000 drops/s, largest drops at the densest region
- Agreement is poor when: Drop size distribution is wide, there is strong correlation between velocity and size.
- Results from PDA does not provide smooth contours typical in these injectors even for fine grid size
PDA vs Patternator (Agreement)

Calculated Absorption Contour Plot

Patternators Extinction

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Sample Results SPIV

GDI Injector at 20 MPa

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Comparison with PDA

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Comparison with PDA

- Reasonable agreement at lower pressure (12 MPa)
- Less agreement at 20 MPa
- PDA results biased with slow moving drops at the end of the injection cycle
- During most of the injection event, PDA cannot acquire data due to very high obscuration
Selected Patternator Customers

<table>
<thead>
<tr>
<th>Abbott</th>
<th>General Motors</th>
<th>Hitachi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend Research</td>
<td>Cummins</td>
<td>AVL</td>
</tr>
<tr>
<td>Pfizer</td>
<td>Emcom Technologies</td>
<td>FEV</td>
</tr>
<tr>
<td>S.C. Johnson &amp; Son</td>
<td>Faurecia</td>
<td>Nordson</td>
</tr>
<tr>
<td>Catalytica Energy</td>
<td>Donaldson</td>
<td>Delavan</td>
</tr>
<tr>
<td>Delphi</td>
<td>Proctor &amp; Gamble</td>
<td>Woodward</td>
</tr>
<tr>
<td>Ricardo</td>
<td>Honeywell</td>
<td>Tenneco</td>
</tr>
<tr>
<td>Continental</td>
<td>Bombardier</td>
<td>Synerject</td>
</tr>
<tr>
<td>Eaton</td>
<td>Rolls Royce</td>
<td>Danfoss</td>
</tr>
<tr>
<td>Columbian Chemical</td>
<td>General Electric</td>
<td>Boston Scientific</td>
</tr>
<tr>
<td>United Technologies Aerospace System</td>
<td>Dow Agrosciences Laboratories</td>
<td>Vertex Pharmaceuticals</td>
</tr>
<tr>
<td>Toyota</td>
<td>Bosch LLC.</td>
<td>3M</td>
</tr>
</tbody>
</table>
Quality Assurance of Nozzles
Quality Control Objectives

- Define QC parameters
- Set tolerance limits
- Generate master template
- Compare each nozzle with master template
- Accept/reject nozzle based on patternation result
Sample QC parameter (1): Spray Angle

Measurement plane

Nozzle

X

Distance (mm)

Distance (mm)

0.0107
0.0082
0.0076
0.0061
0.0046
0.0031
0.0015
0.0000

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Sample QC parameter (2): Angular Distribution

- **Maximum distance**
  \[ \Delta \Gamma_{\text{Max}} = \left| S^i_t - S^i_m \right| \]

- **L2 Norm**
  \[ L_2 = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (S^i_t - S^i_m)^2} \]
Sample QC Parameter (3): Radial Uniformity

- **Maximum distance**
  \[ \Delta X_{\text{Max}} = \left| S_t^i - S_m^i \right| \]

- **L2 Norm**
  \[ L_2 = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (S_t^i - S_m^i)^2} \]
Quality audit configuration

- Control Panel PC
- Ethernet switch
- Ethernet/Serial converter
- SQL database PC
- Patternator PC
- Data cable
- Ethernet cable
- Spray gun
- Optical Patternator

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Sample Report Generated by SETscan

Optical Patternation Report

Patternation Plot

Radial distribution plot

Contour Plot

Angular distribution plot

Master template limits
1. Angle: A1 – A2
2. L2 Norm Radial: B1 – B2
3. L2 Norm Axial: C1 – C2
4. Deviation angle: D1 – D2
5. Max. radial distance: E1 – E2
6. Max. axial distance: F1 – F2
7. Tolu surface area: G1 – G2

Measured values
1. Angle: A
2. L2 Norm Radial: B
3. L2 Norm Axial: C
4. Deviation angle: D
5. Max. radial distance: E
6. Max. axial distance: F
7. Tolu surface area: G

Standard nozzle report
Code No:
Operator No.
Nozzle No.
Date:

SETScan OP-606 patternator

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Sample Installation (OP-600)

- 2 computer QA system
- Automatic nozzle mounts
- Booth by Alsmatik
- QA software by En’Urga
- Multiple types of nozzles
- Typical output: 1000/day

Photograph: Courtesy Danfoss S/A

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Product Quality Implications

- On-line 100% inspection of nozzles enabled
- Traceable and warehoused data
- Quick design verification tool
- Sorting of already manufactured nozzles
Selected Customer Comments

“We purchased the patternator and in six months we approached our customer with a request to tighten tolerances on the nozzles we produce”

“The SETscan patternator has given us an order of magnitude return on investment within one year after we purchased it”

“The first time I saw the patternation results obtained with our nozzles on the SETscan, I was amazed. I did not realize what was possible with current technology”

“Our department will most probably win the improved productivity award of our company, thanks in a large measure to the SETscan patternator”