Spray Characterization

An Overview

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En'Urga Inc.

innovations in quality control

SETscan®

Outline

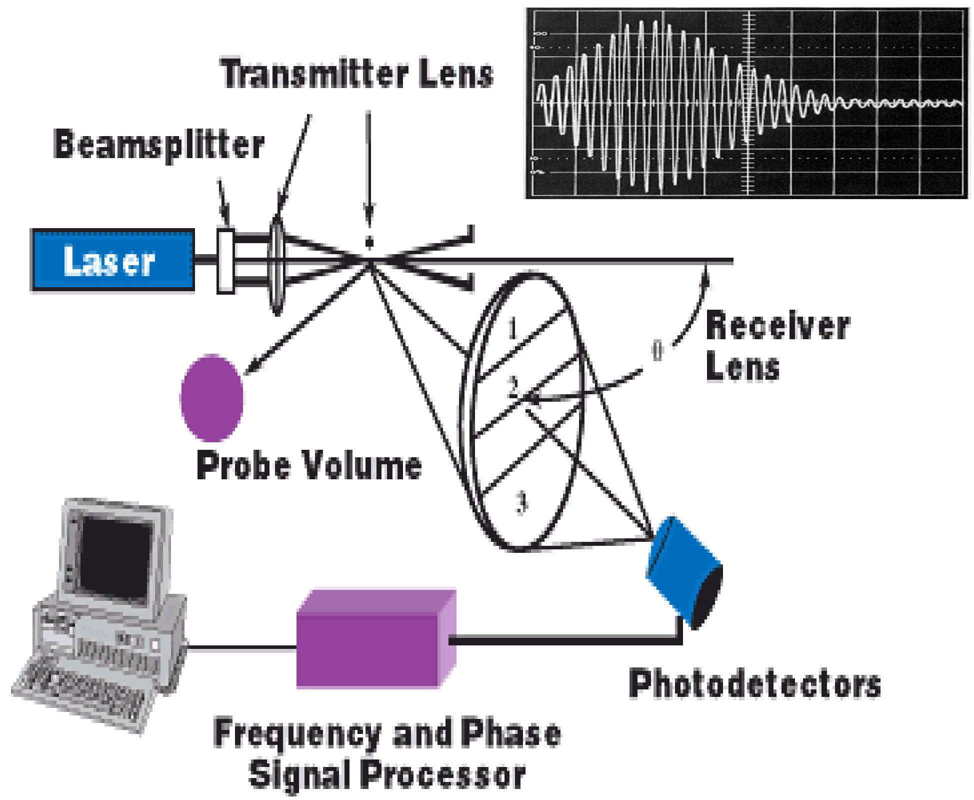
- **Spray Characterization Methods**
- **Sample Results**
- **Quality assurance using optical patternator**

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*

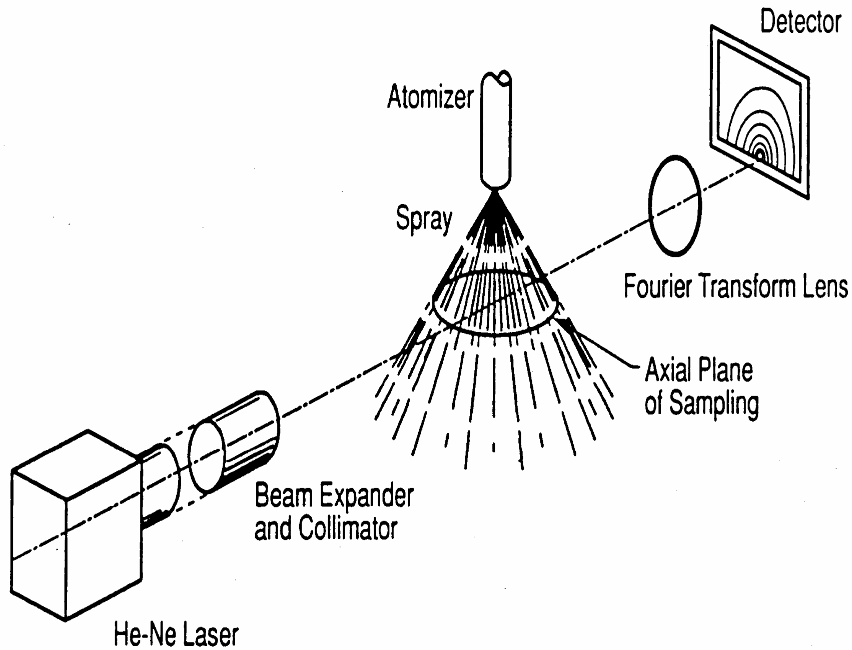


Measurement Characteristics

Aerosol limitations	Spherical, transparent/opaque
Distance to sample	< 3m
Probe volume	small
Size	1-500μm
Number limitation	Coincident, extinction
Sampling type	Flux dependent
Measured quantities	Velocity, size
Dynamic range	50
Sampling mode	Time averaged, time resolved
Sensitivity highest	large drops

Fraunhofer Diffraction

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

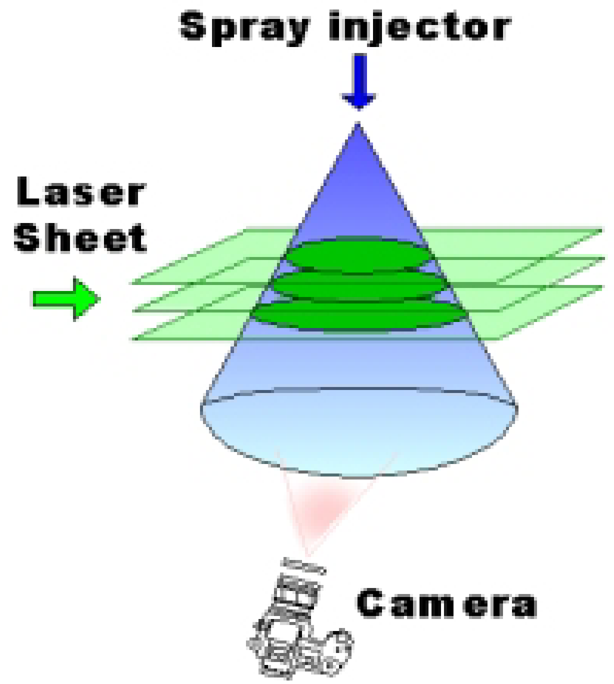


Measurement Characteristics

Aerosol limitations	None on shape/better if opaque
Distance to sample	< 0.5 m
Probe volume	Line of sight
Size	0.3-500 μm
Number limitation	Extinction, multiple scattering
Sampling type	Concentration
Measured quantities	Size
Dynamic range	100
Sampling mode	Time averaged, time resolved
Sensitivity highest	Middle range of drop sizes

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



<u>Potential Errors</u>

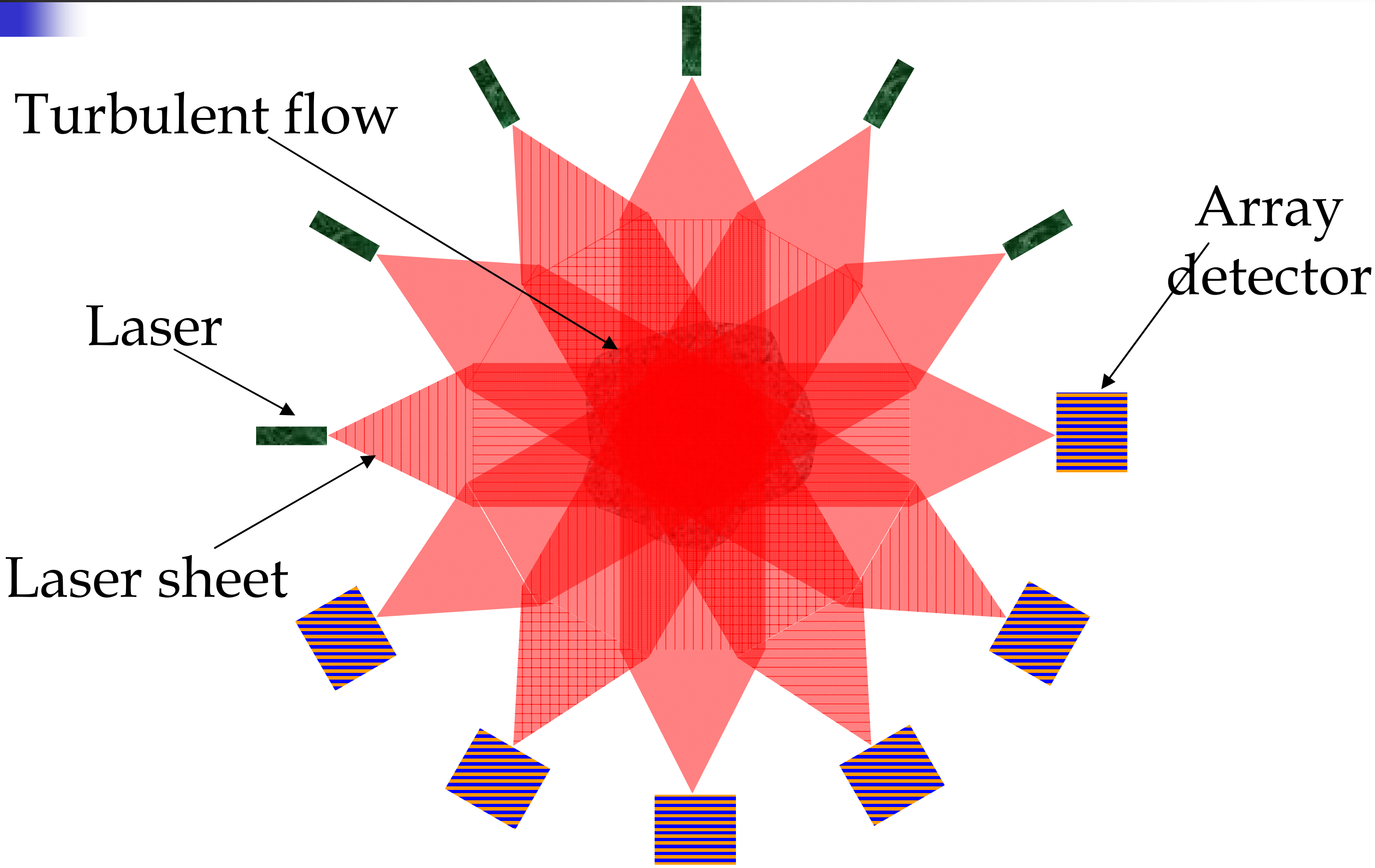
- Laser extinction
- Signal attenuation
- Secondary emission

Implication: Qualitative patternation

Measurement Characteristics

Aerosol limitations	Spherical particles
Distance to sample	< 0.5 m
Probe volume	Planar, volume
Size	3-unlimited
Number limitation	Extinction, image overlap
Sampling type	Concentration dependent
Measured quantities	Light intensity
Dynamic range	20
Sampling mode	Instantaneous
Sensitivity highest	Largest drops

Extinction Tomography (SETscan)



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

Aerosol limitations	Unrestricted
Distance to sample	Unrestricted
Probe volume	Planar
Size	Unrestricted
Number limitation	Extinction
Sampling type	Concentration
Measured quantities	Surface area * no. of drops/m^3
Dynamic range	Instrument SNR
Sampling mode	Instantaneous, time averaged, time resolved
Sensitivity highest	Uniform across range

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

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

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

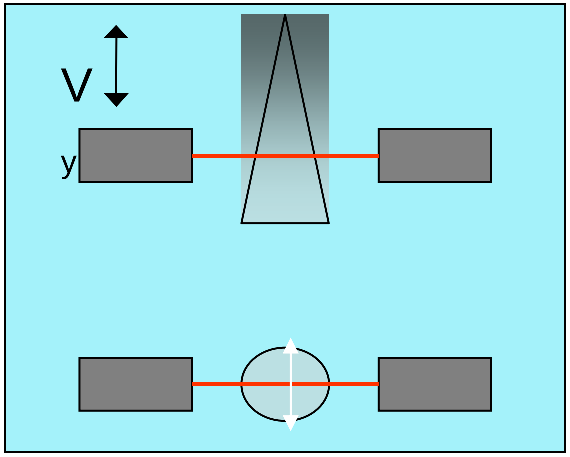
- Does not require distinct particles
- Works with various types of lighting such as shadowgraphy and natural lighting
- Work equally well with dense sprays
- High powered lasers not required

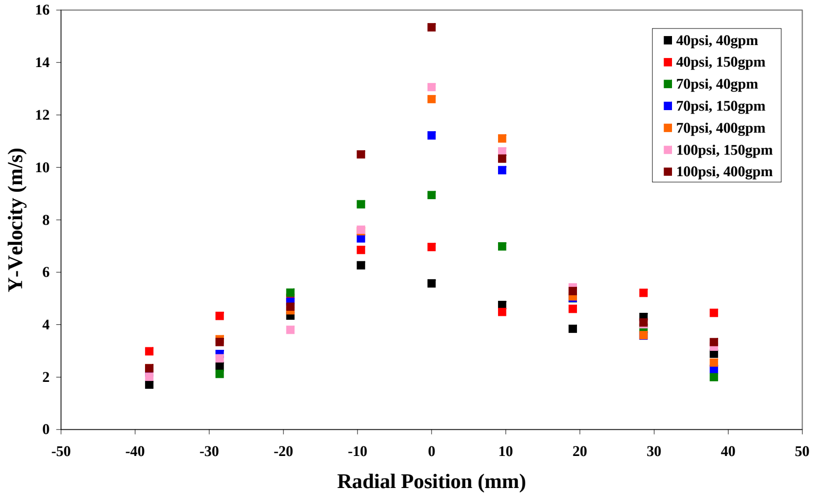
Disadvantages

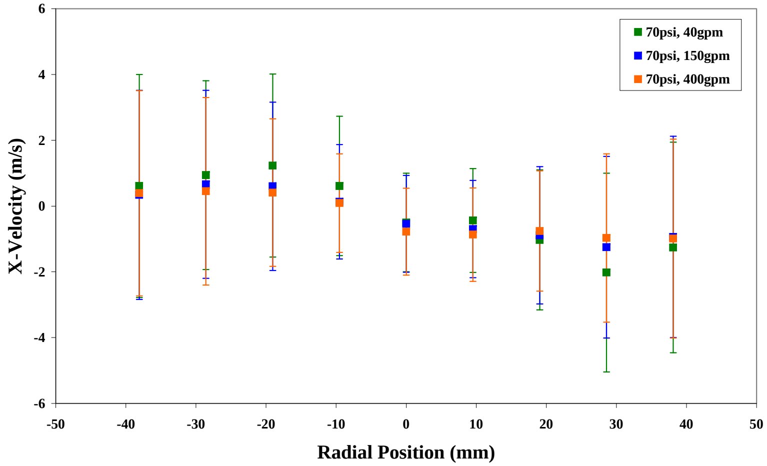
- Bimodal velocity difficult to resolve
- Longer computational time required
- Minimum 10 KHz camera

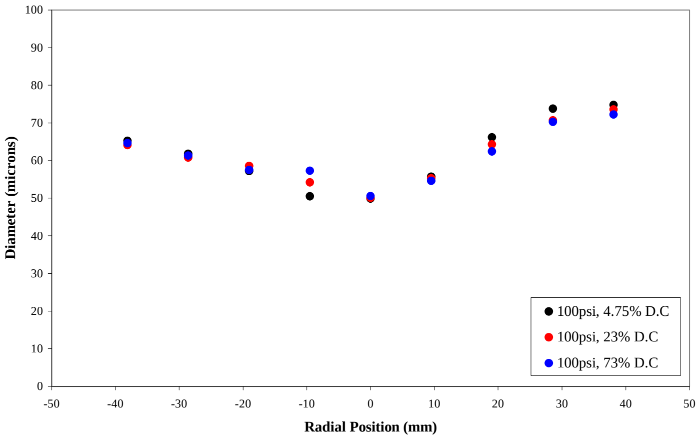
Sample Results

Sample Results (PDA)









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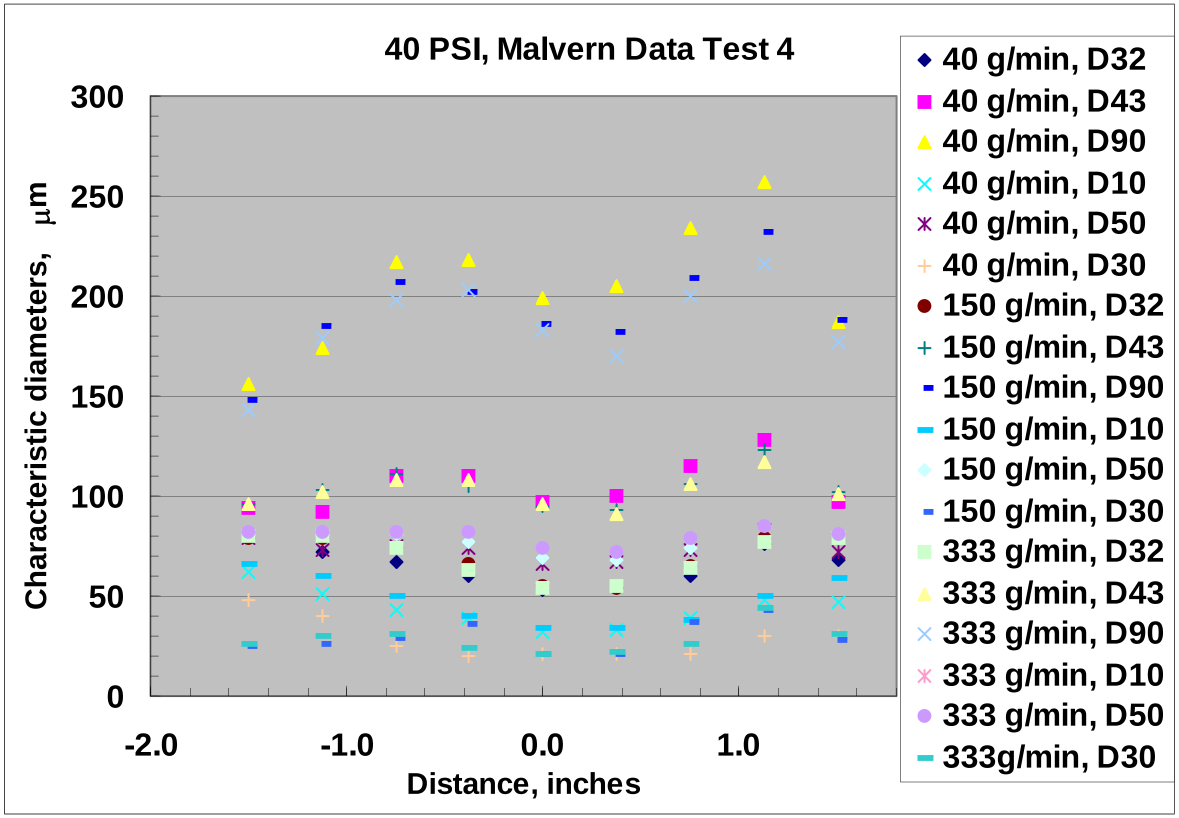
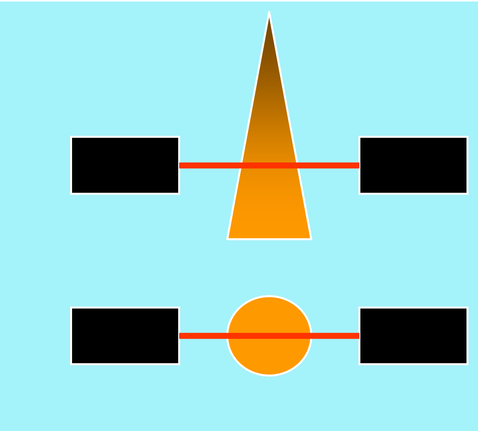
Sample Results (Malvern)

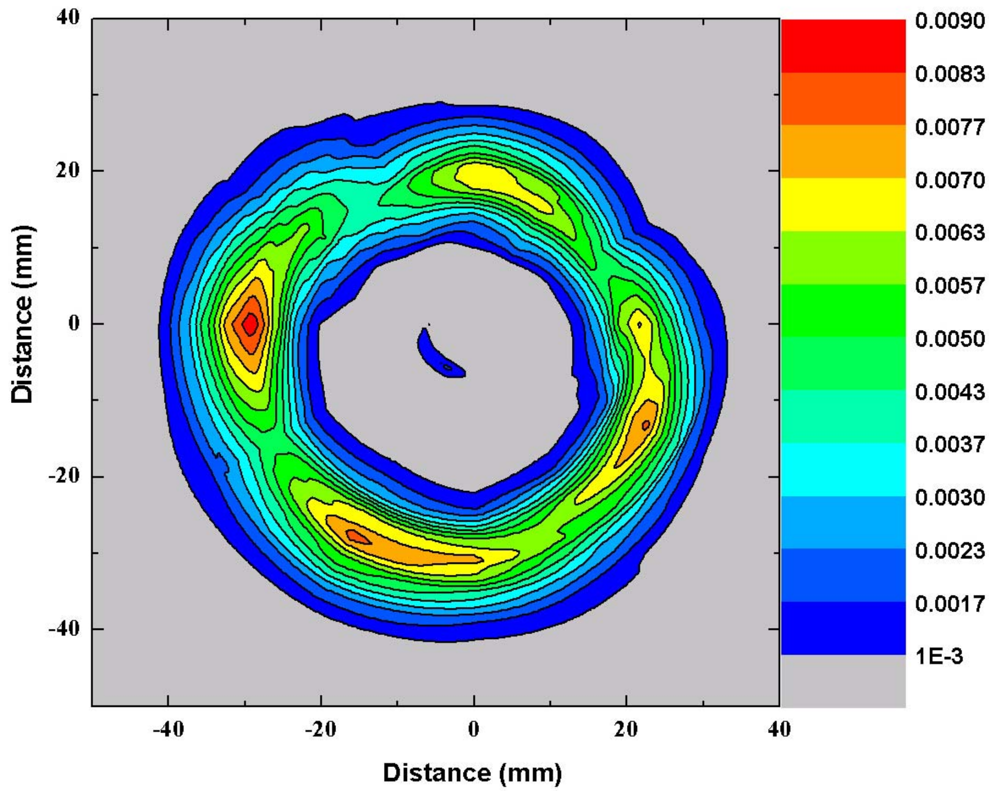




- Single line data
- Two data points at each condition

Sample Results Patternator

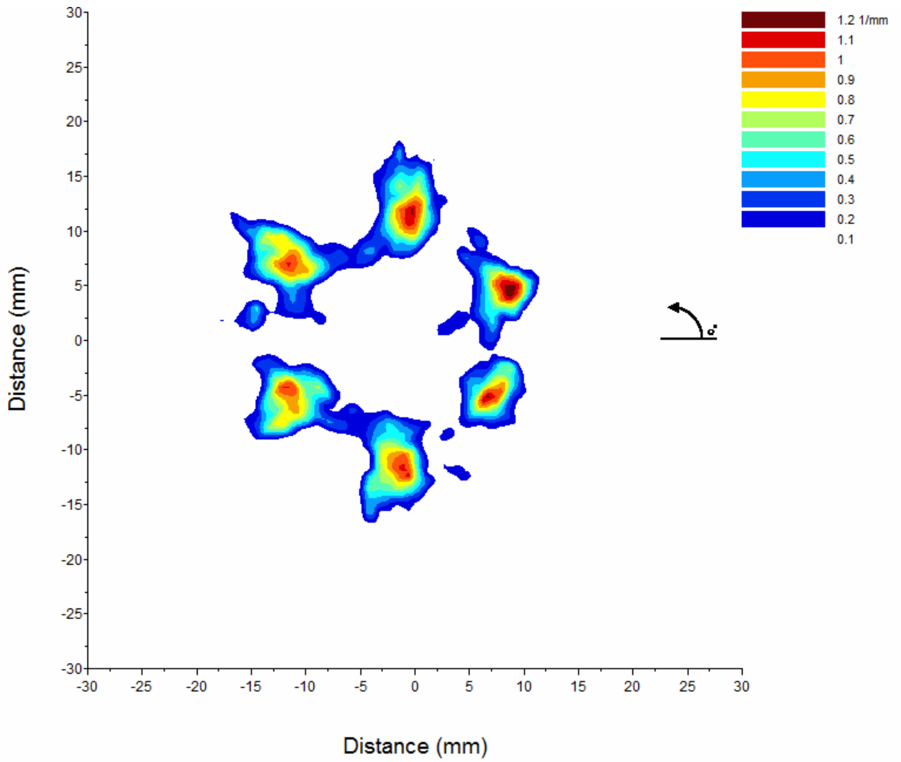
- Struts signature seen in drop surface area map
- Hollow cone seen as hollow
- Drip from nozzle seen at the center



Automotive Injector

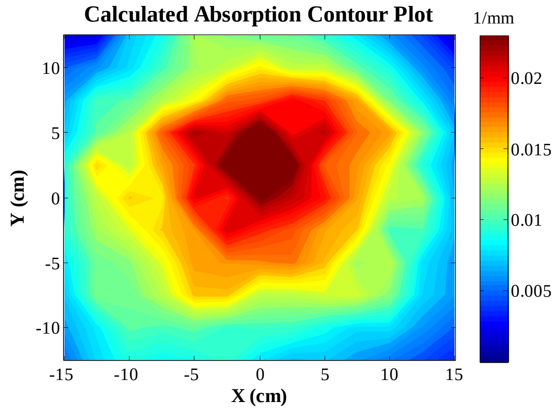
Mean plume angles (deg.)	% area in plume
10.89	19.32
5.73	4.69
11.53	21.71
10.48	17.91
11.51	23.06
9.35	12.93

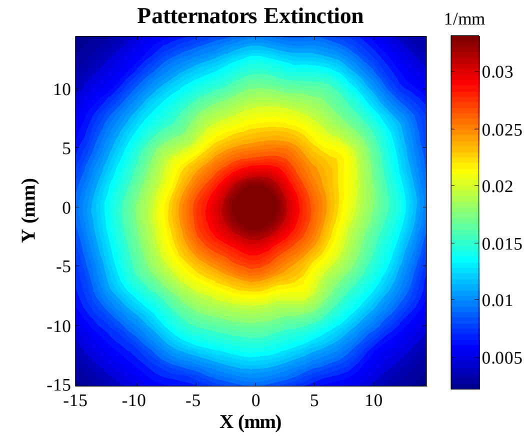
Mean centroid (x, mm)	Mean centroid (y, mm)
3.26	-5.69
-4.84	14.28
-22.13	1.97
-29.04	-10.75
-15.37	-18.49
0.10	-20.01

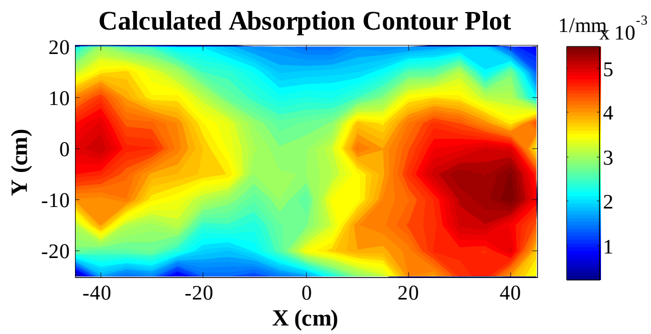


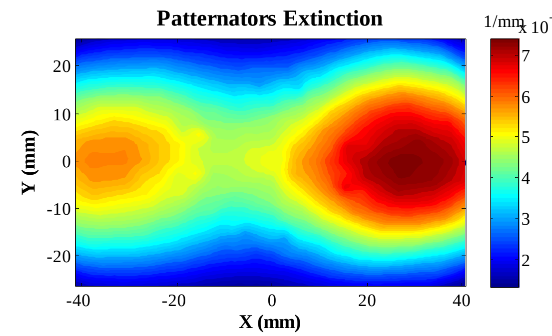
Reliable data with multiple orifice injectors

PDA vs Patternator (Agreement)

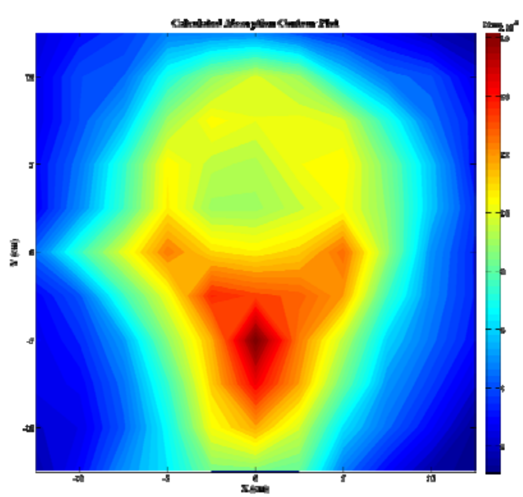


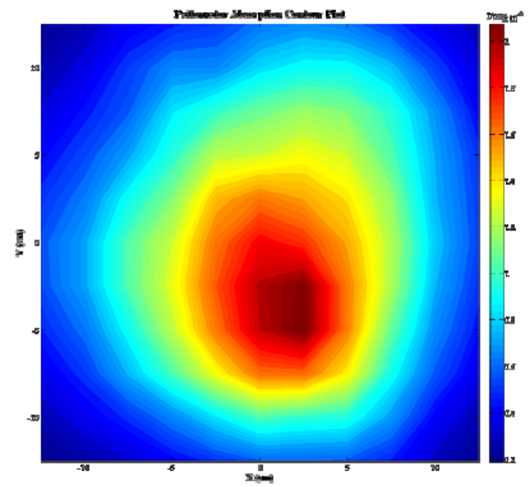






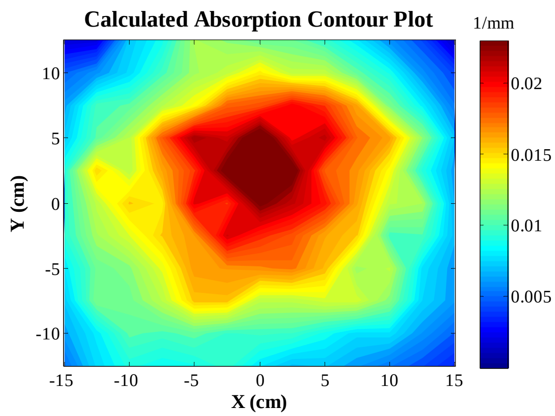
PDA vs Patternator (Discrepancy)

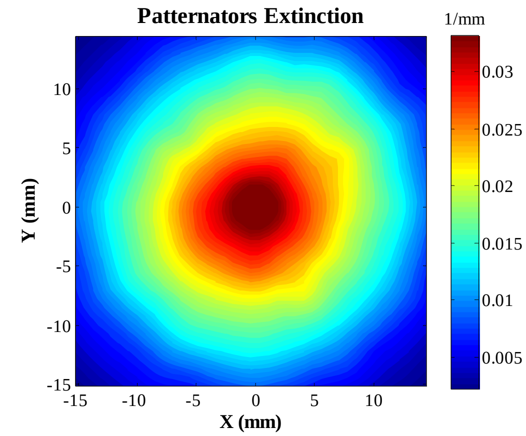


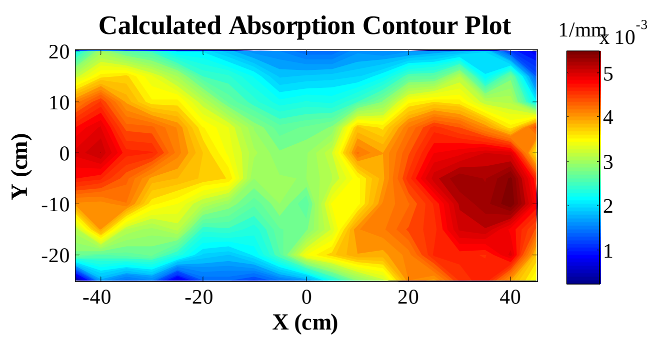


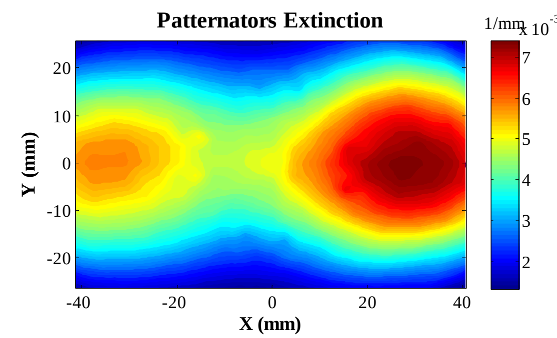
- Agreement (within 20% – 30%) when: Data-rate < 30,000 drops/s, largest drops at the densest region
- Agreement is poor when: Drop size distribution is wide, there is strong correlation between velocity and size.
- Results from PDA does not provide smooth contours typical in these injectors even for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

PDA vs Patternator (Agreement)

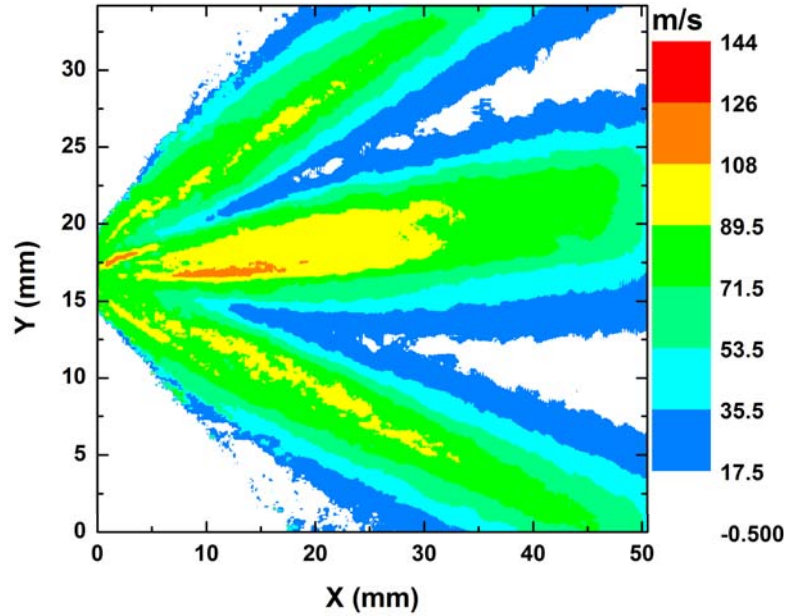


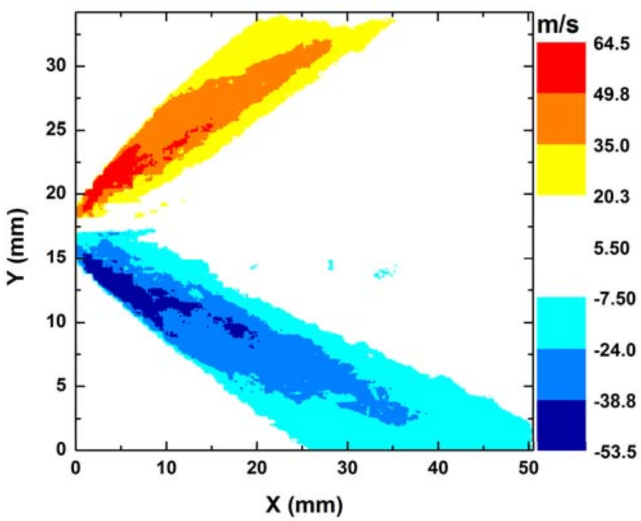






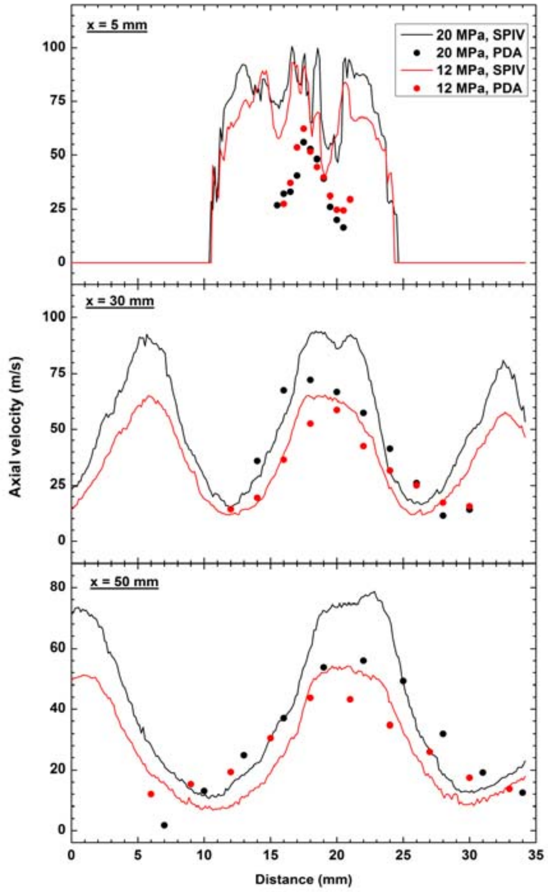
Sample Results SPIV

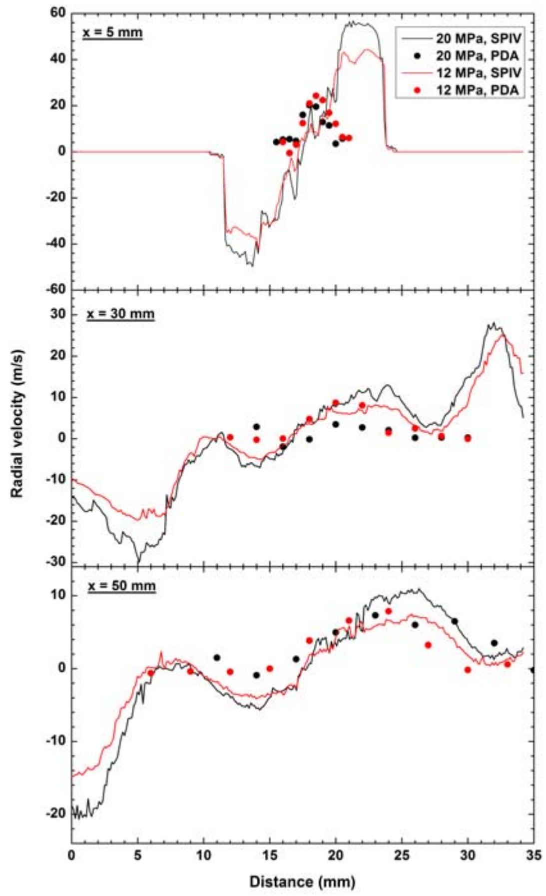




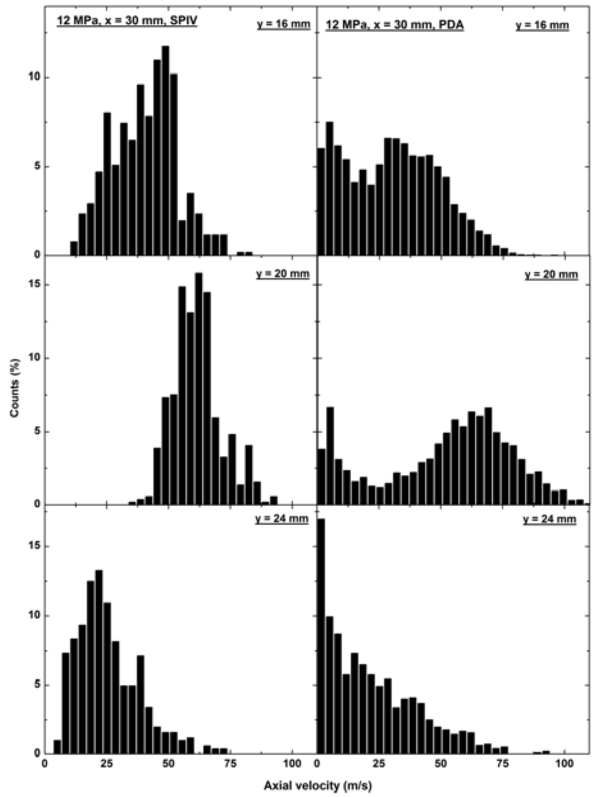
GDI Injector at 20 MPa

Comparison with PDA





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

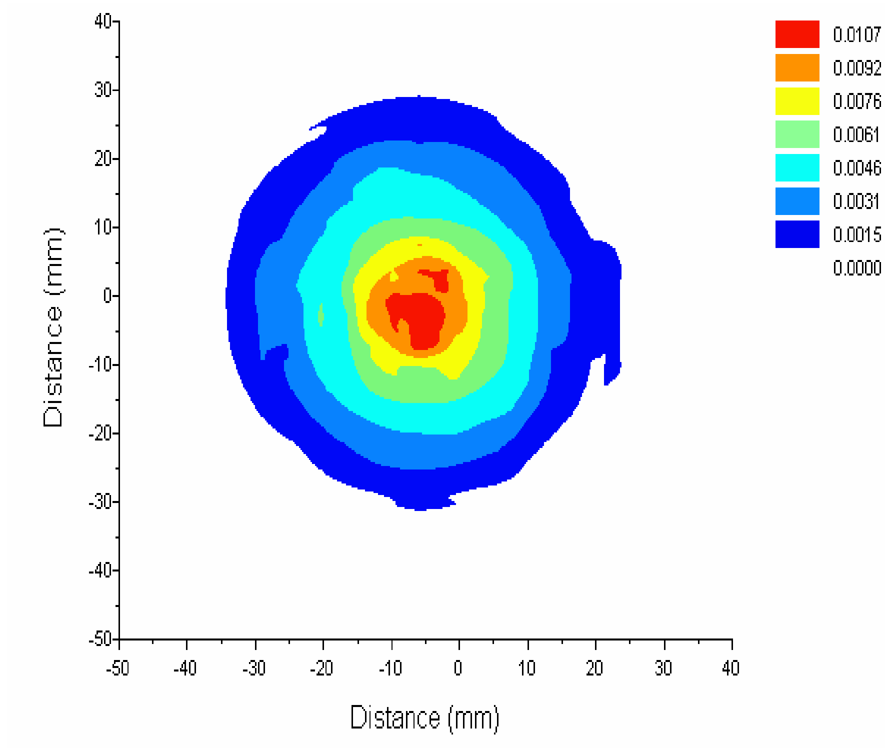
Abbott	General Motors	Hitachi
Bend Research	Cummins	AVL
Pfizer	Emcom Technologies	FEV
S.C. Johnson & Son	Faurecia	Nordson
Catalytica Energy	Donaldson	Delavan
Delphi	Proctor & Gamble	Woodward
Ricardo	Honeywell	Tenneco
Continental	Bombardier	Synerject
Eaton	Rolls Royce	Danfoss
Columbian Chemical	General Electric	Boston Scientific
United Technologies Aerosapce System	Dow Agrosciences Laboratories	Vertex Pharmaceuticals
Toyota	Bosch LLC.	3M

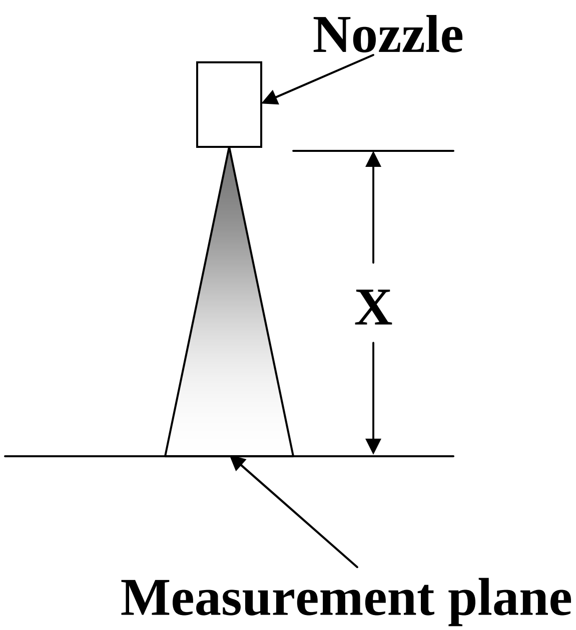
Quality Assurance of Nozzles

Quality Control Objectives

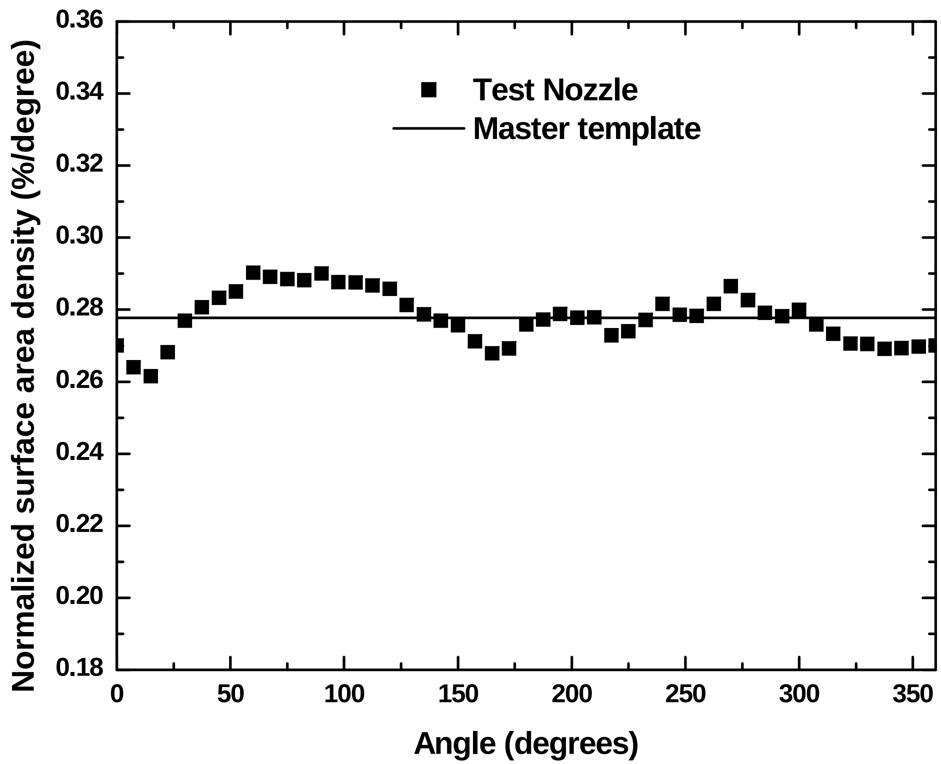
- Define QC parameters
- Set tolerance limits
- Generate master template
- Compare each nozzle with master template
- Accept/reject nozzle based on patternation result

Sample QC parameter (1): Spray Angle





Sample QC parameter (2): Angular Distribution



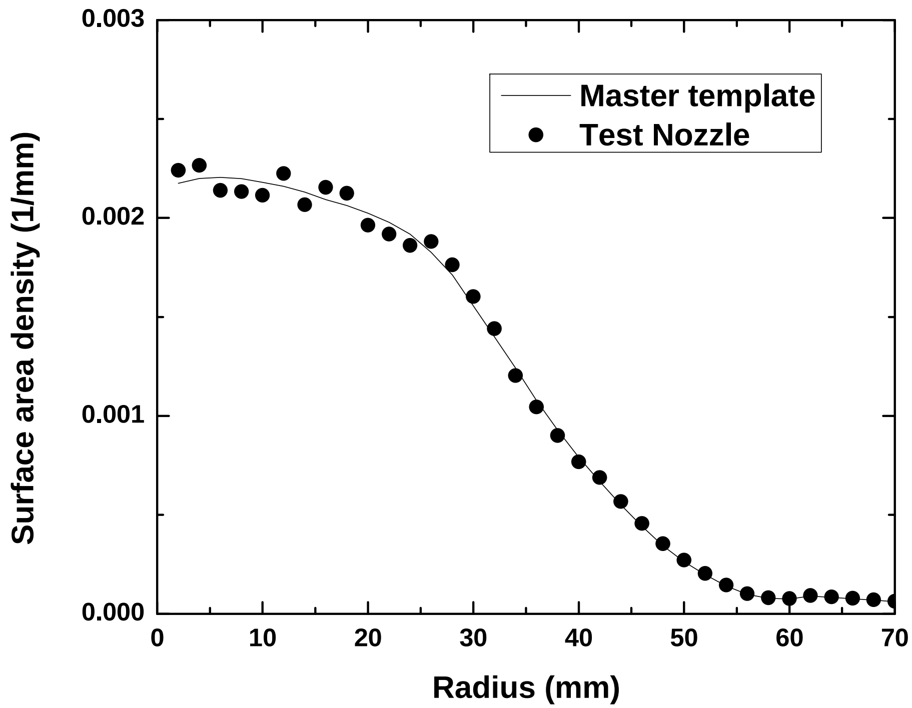
- **Maximum distance**

$$\Delta\Gamma_{Max} = \left| S_t^i - S_m^i \right|$$

- **L2 Norm**

$$L_2 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_t^i - S_m^i)^2}$$

Sample QC Parameter (3): Radial Uniformity



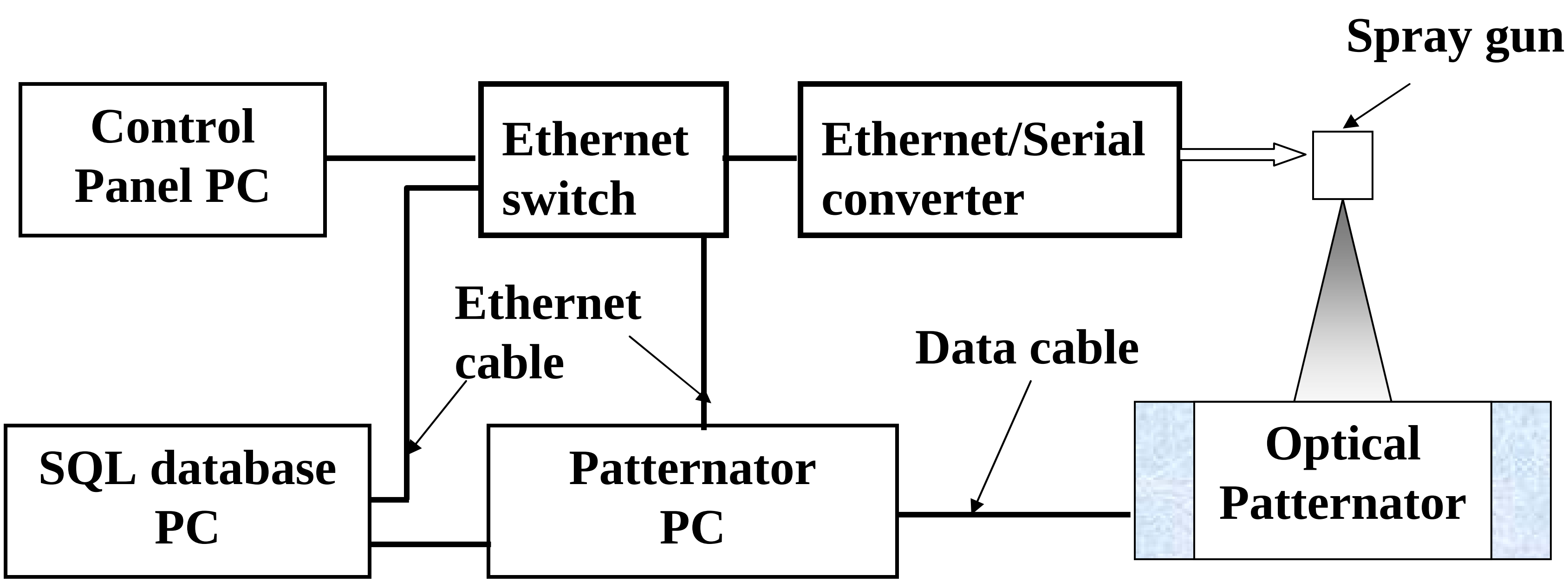
- **Maximum distance**

$$\Delta X_{Max} = \left| S_t^i - S_m^i \right|$$

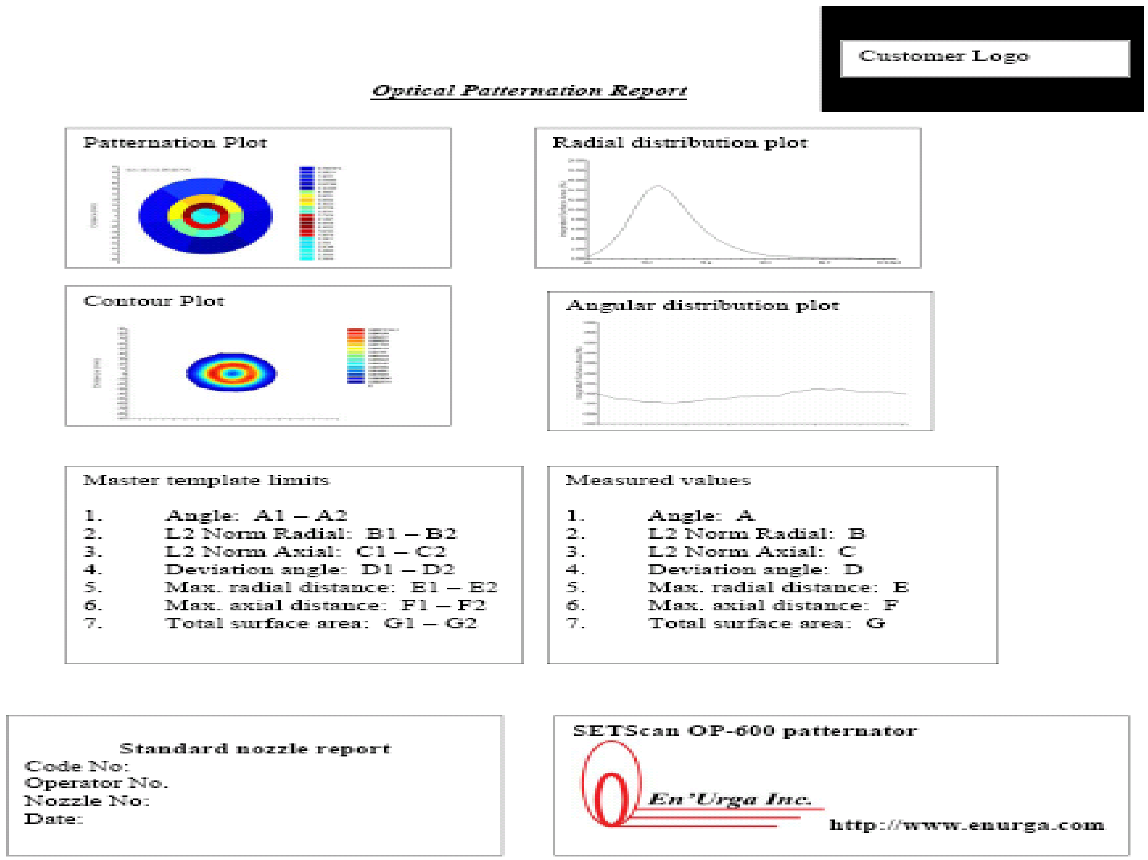
- **L2 Norm**

$$L_2 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_t^i - S_m^i)^2}$$

Quality audit configuration



Sample Report Generated by SETscan


Customer Logo

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. Total 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. Total surface area: G

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

SETScan OP-600 patternator
En'Urga Inc.
http://www.enurga.com

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

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"