Characterization Methods for Spray Drying Nozzles

An Overview

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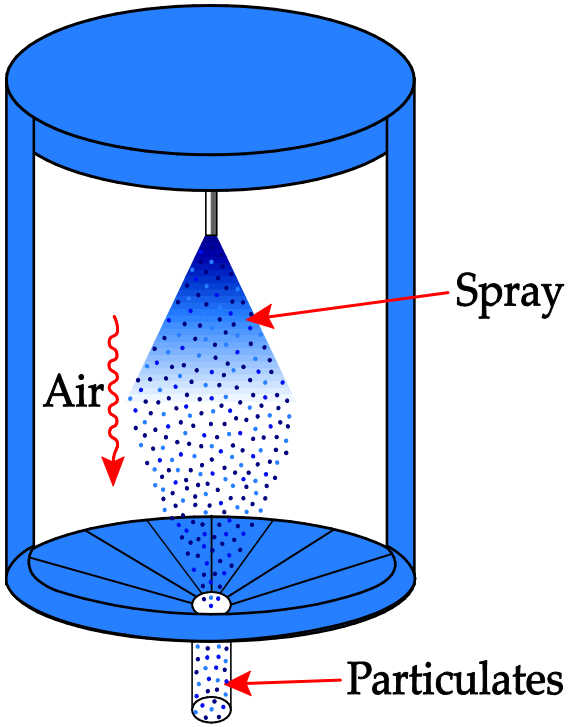
Motivation

- Spray drying used for producing powder from a liquid or slurry
- Food, pharmaceuticals, consumer products
- Can convert APIs from crystalline to amorphous form for improved bio-availability
- All spray dryers use some type of nozzles
- Quality of nozzle determines the final product quality



Outline

- Spray Characterization Methods
- Sample Results
- Spray characterization work at En'Urga Inc.

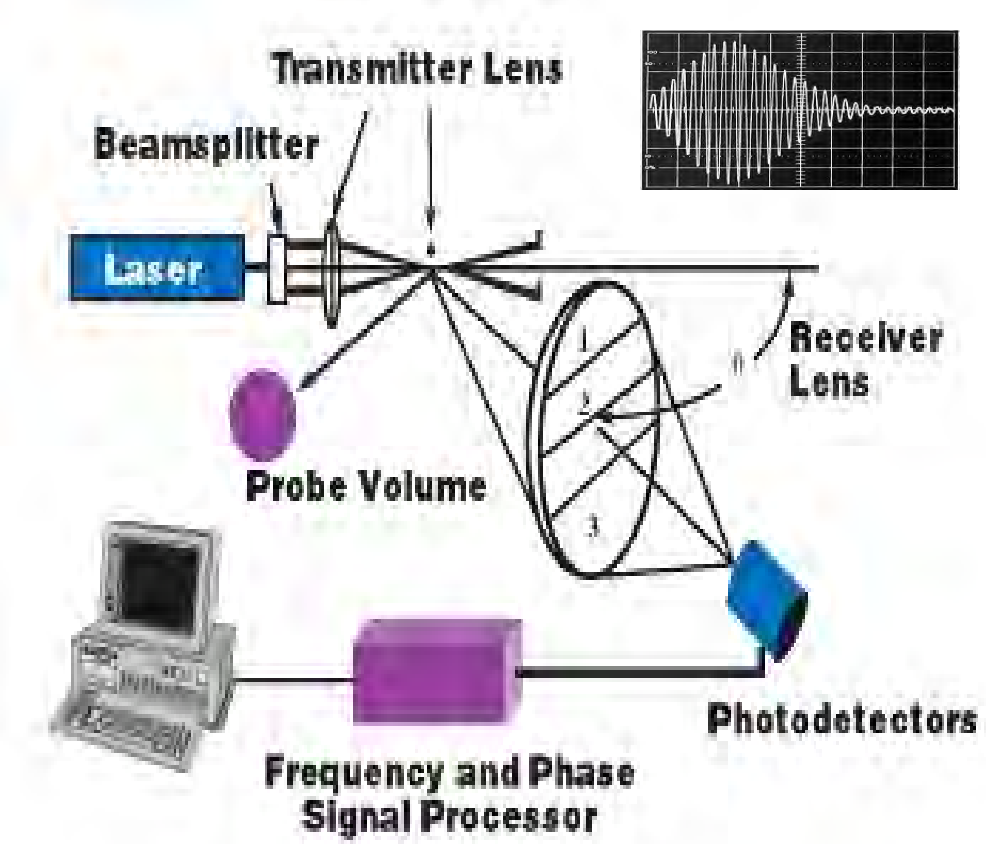
Spray Characterization Methods

Spray Characterization Methods

- Phase Doppler interferometry
- Fraunhofer diffraction
- Laser sheet imaging
- Extinction tomography
- Imaging velocimetry
- Holographic imaging
- Laser induced Fluorescence
- X-Ray visualization

Phase Doppler Interferometry

- Fringe pattern from 2 laser beams
- Particle scatters light and projects pattern
- Detector at one angle provides velocity
- Multiple detectors provide size
- Multiple setting required for wide dynamic range



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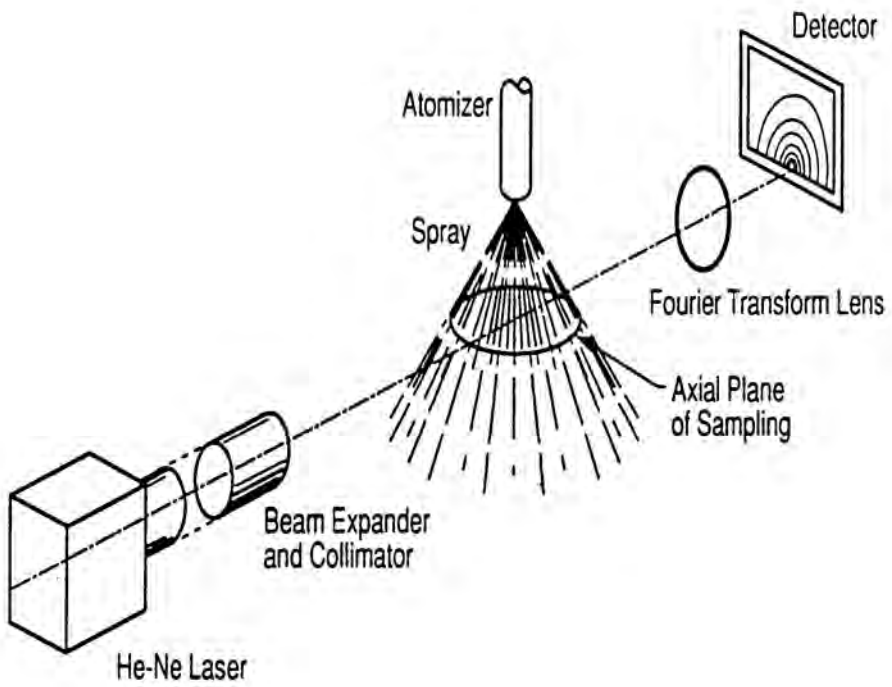
Measurement Characteristics

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
- Fourier transform lens for discrimination
- Array detectors measures intensity at different angles
- Mie scattering theory for particle size
- Beam wandering a problem in evaporating fluids

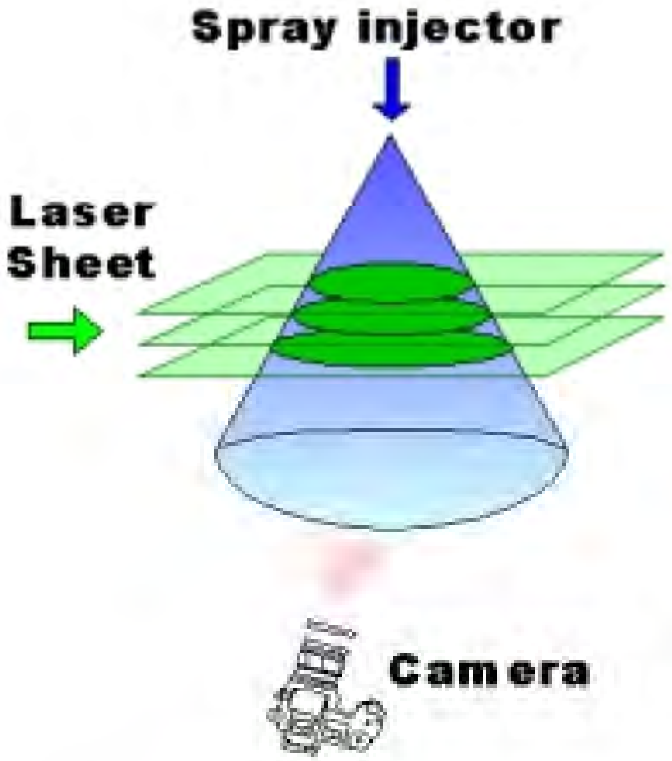


Measurement Characteristics

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



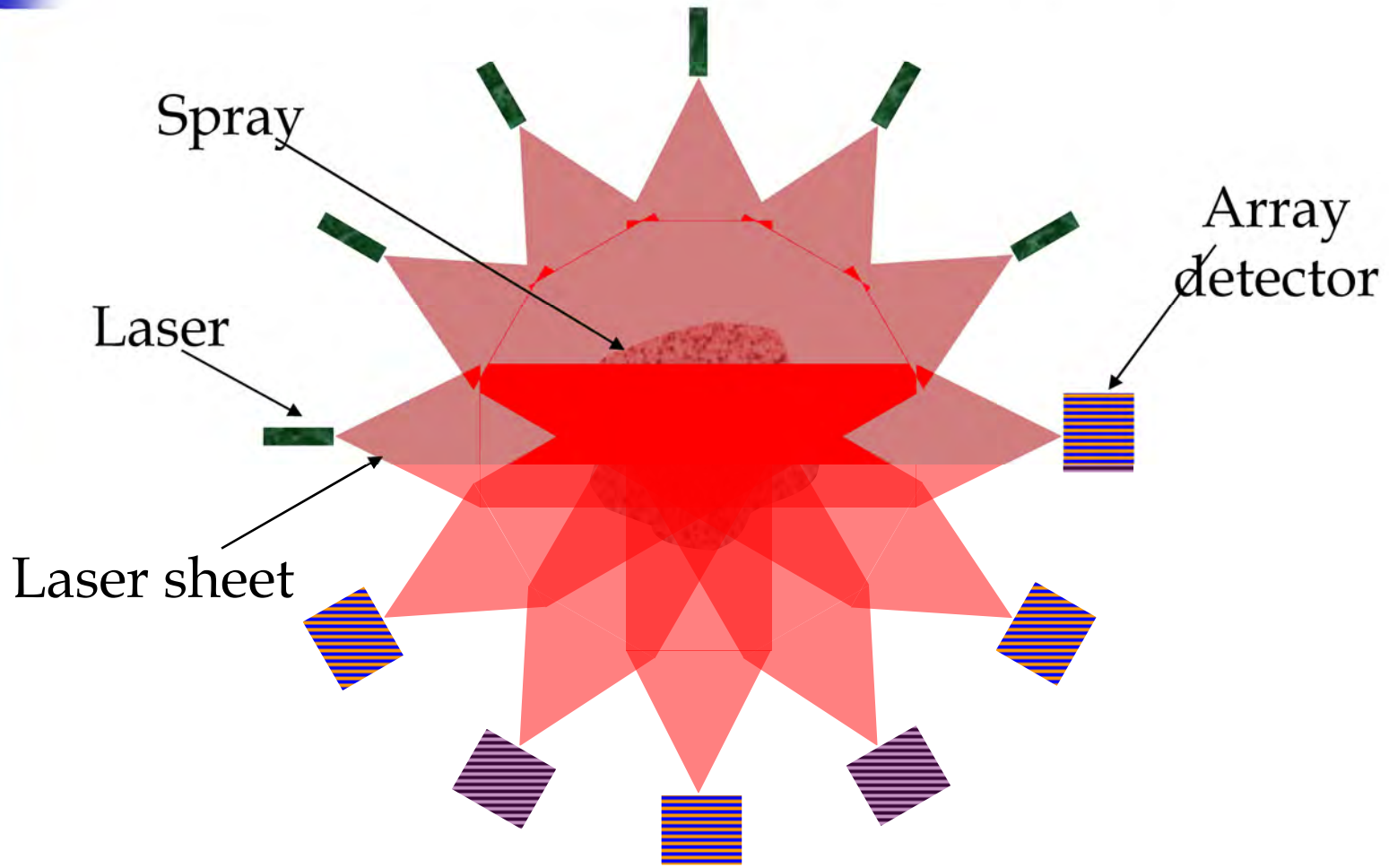
Potential Errors

- Laser extinction
- Signal attenuation
- Secondary emission

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**

Imaging Velocimetry

- Two types available
- 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

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Advantages and Disadvantages of SPIV

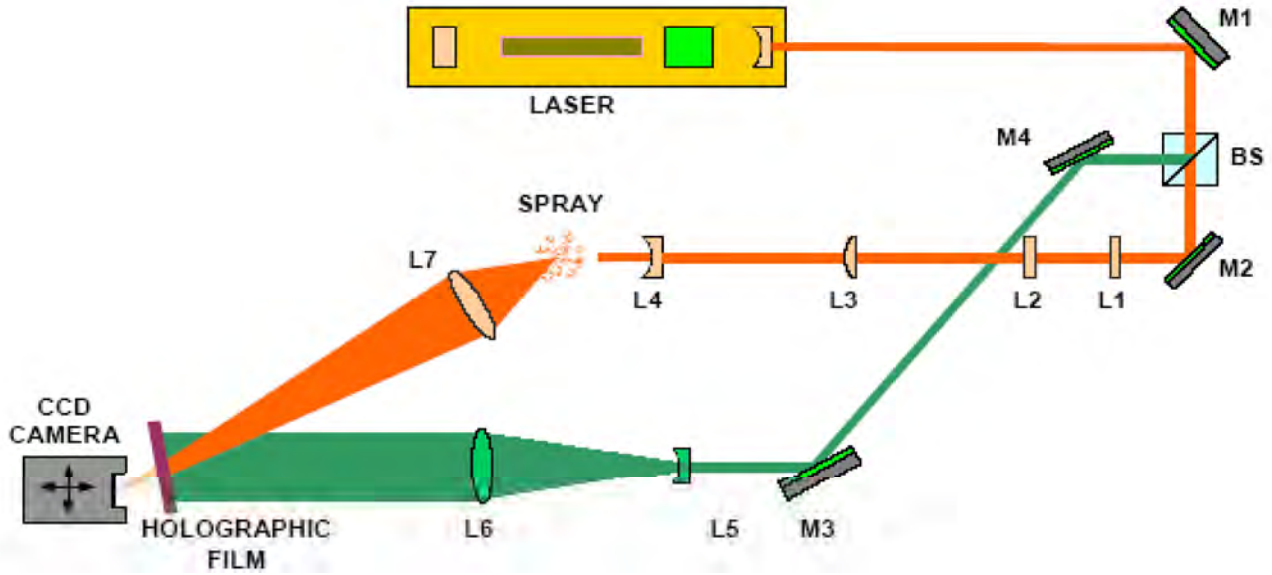
Advantages

- 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

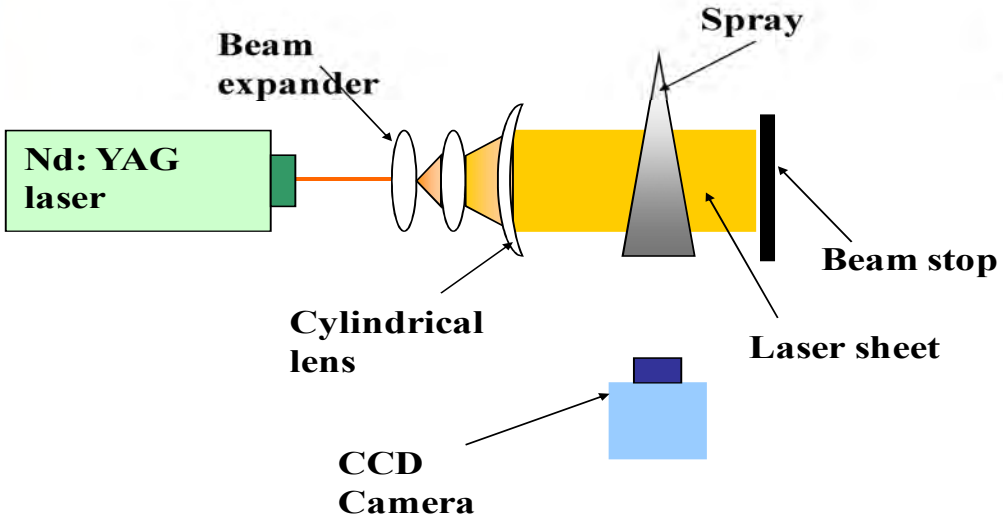
Holographic Imaging



- *Scattered or shadow images mixed with a reference beam*
- *Interference pattern on holographic film*
- *Image reconstructed to obtain particle size/shape*

Planar Laser Induced Fluorescence

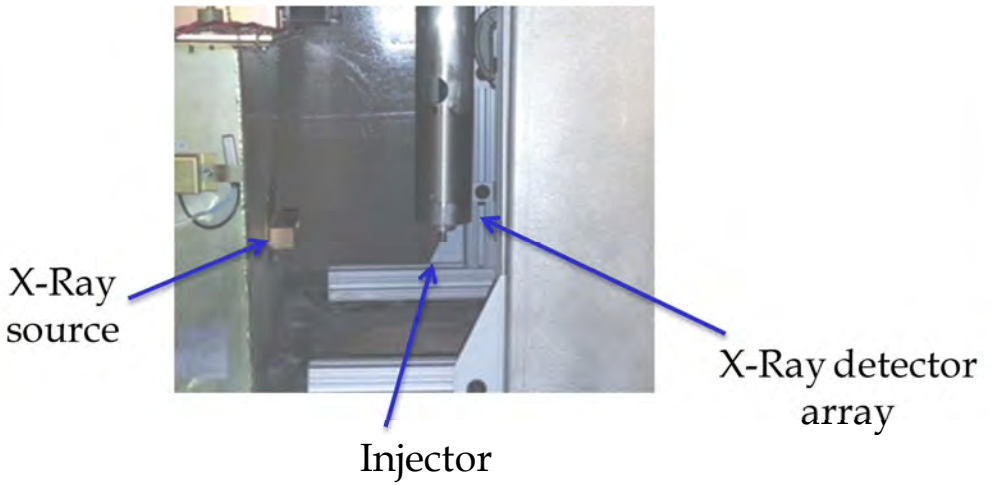
- Fuel, sometimes mixed with Dopant
- Excited with laser sheet
- Fluorescence observed with CCD array
- Intensity proportional to volume fraction



Potential Errors

- Laser extinction
- Signal attenuation
- Shot-to-shot variation

X-Ray visualization



- Ideal for dense sprays (light cannot penetrate)
- Used to obtain planar mass concentration
- Works with particles, gases, and liquids

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/	Instantaneous/	Instantaneous	Time Ave, Time
	Time Resolved	Time Reolved		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

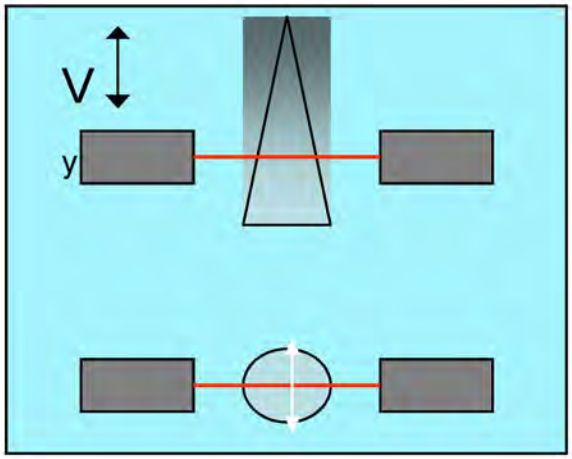
Why surface area density

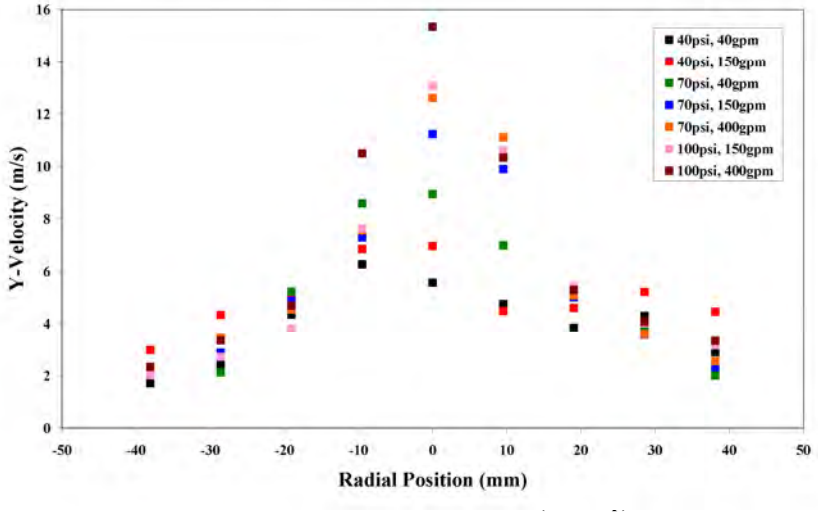
- Total amount of fuel or liquid evaporated is proportional to heat release rate in combustion and solid mass fraction in spray drying.
- Correlation coefficient (R) of different parameters with total fuel evaporated
- Mass flux R = 0.903 Velocity R = -0.239
- Diameter = 0.681 ***Surface area density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

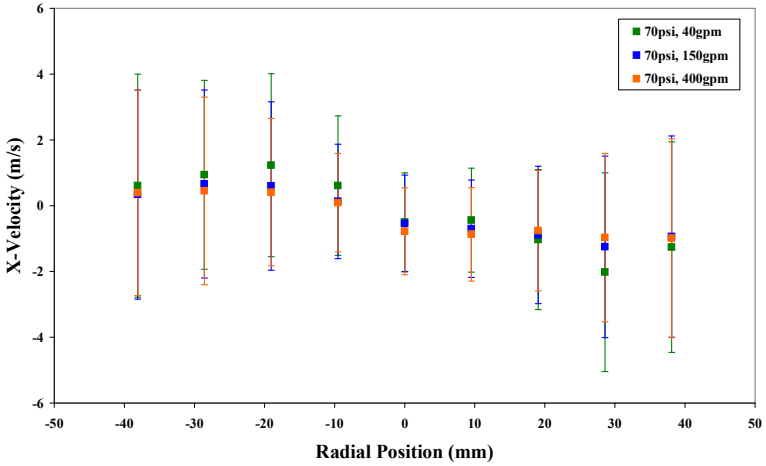
For combustion and spray drying applications, surface area density is optimal method of comparing different nozzles or checking uniformity

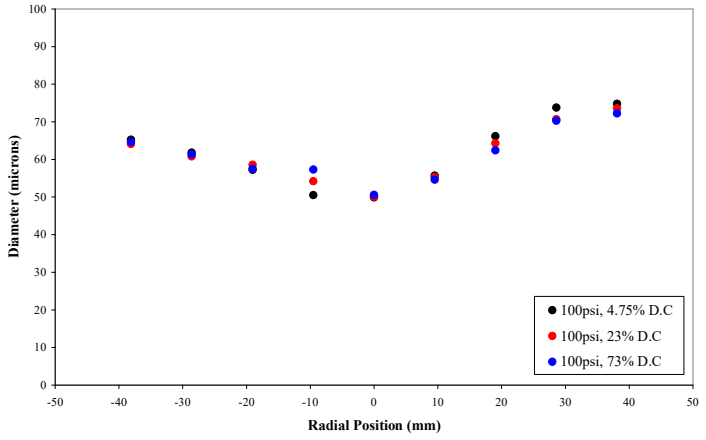
Sample Results

Sample Results (PDA)









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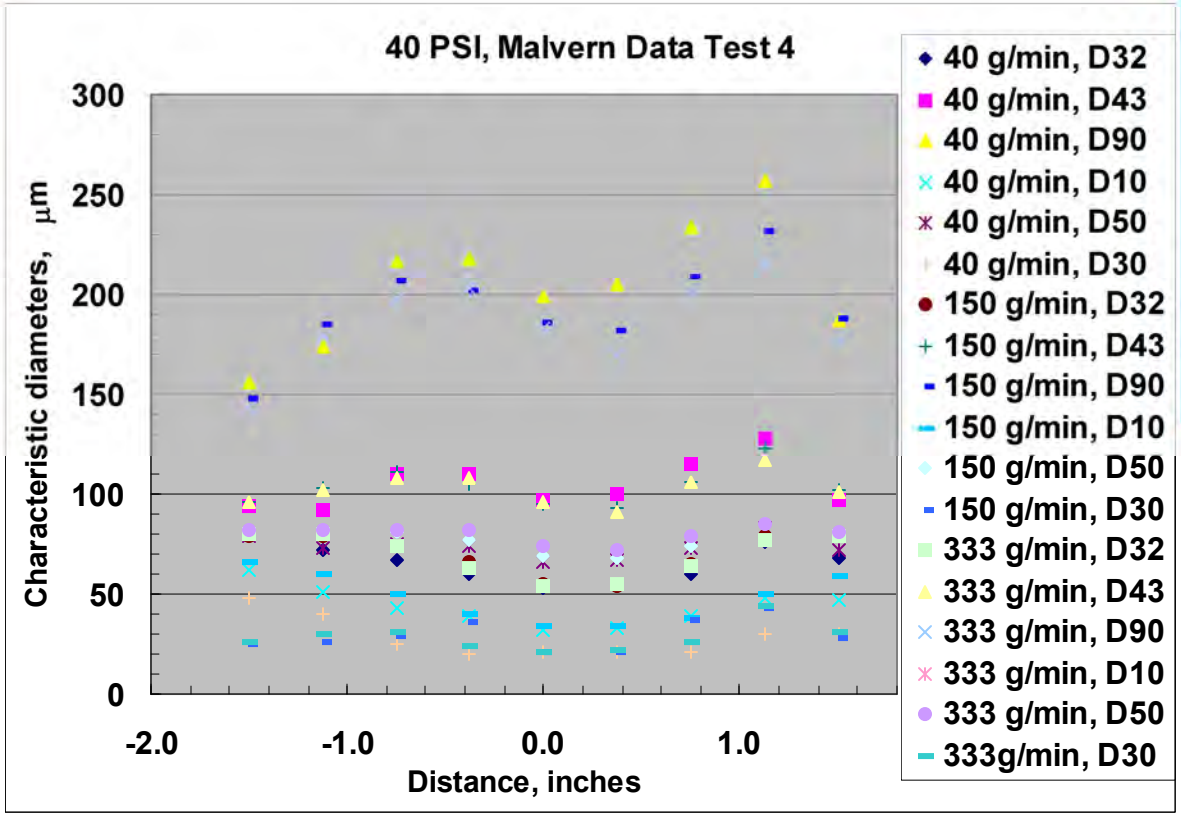
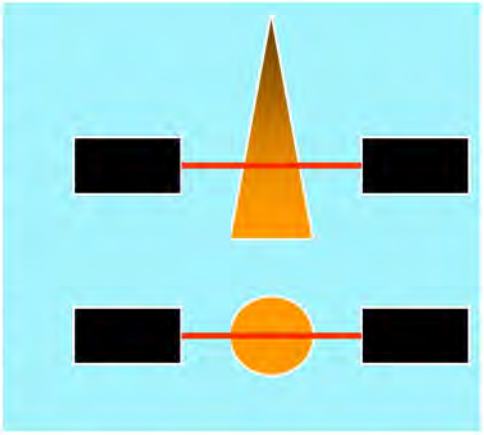
Sample Results (Malvern)





- Single line data
- Two data points at each condition

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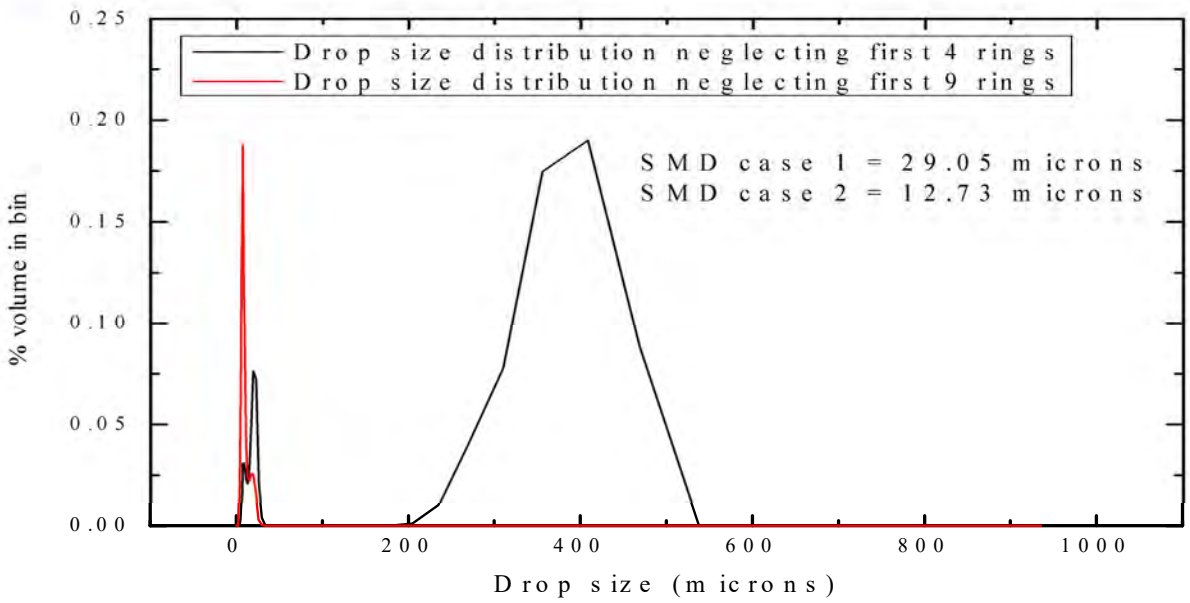
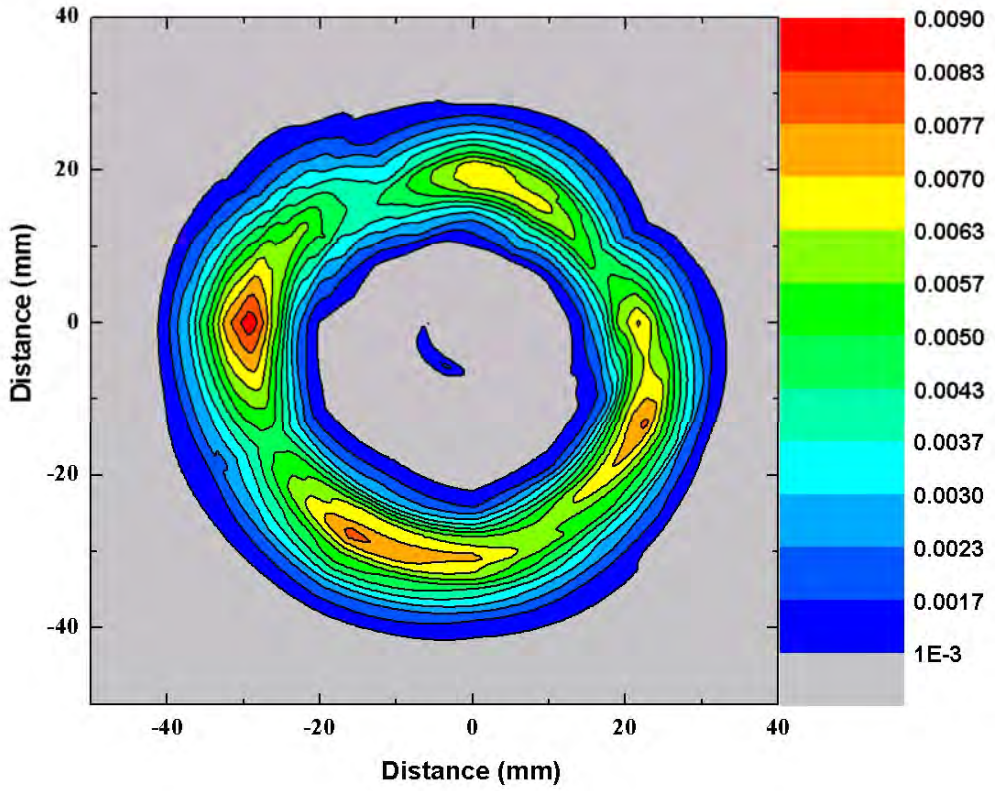
Sample Measurement (effect of vapor)



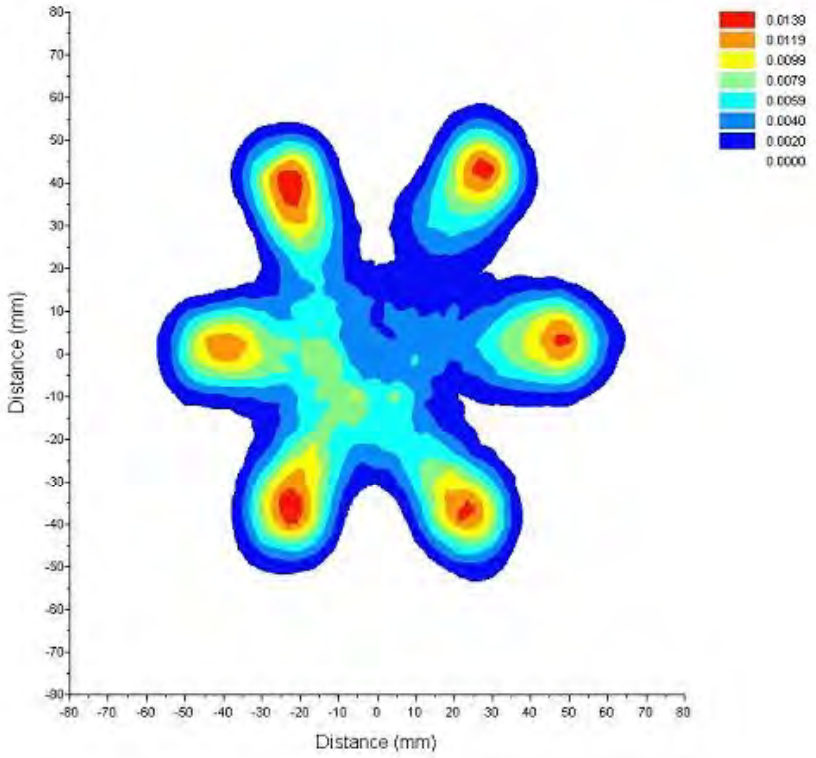
- Effect of fuel vapor (beam wandering) is to cause spurious readings of large drops
- Recommendation is to neglect reading of first 9 rings or all drops larger than 150 microns
- Injector manufactures report

Sample Results Patternator

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



Sample Result: Agricultural Nozzle



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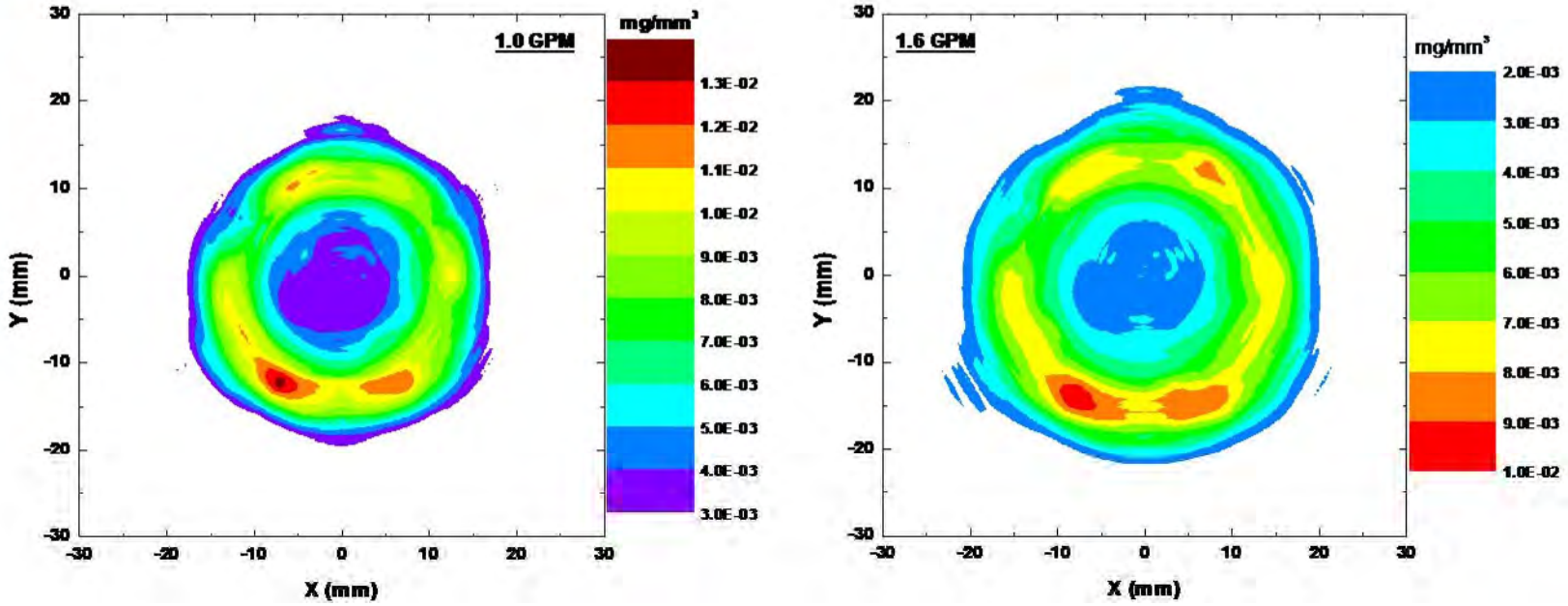
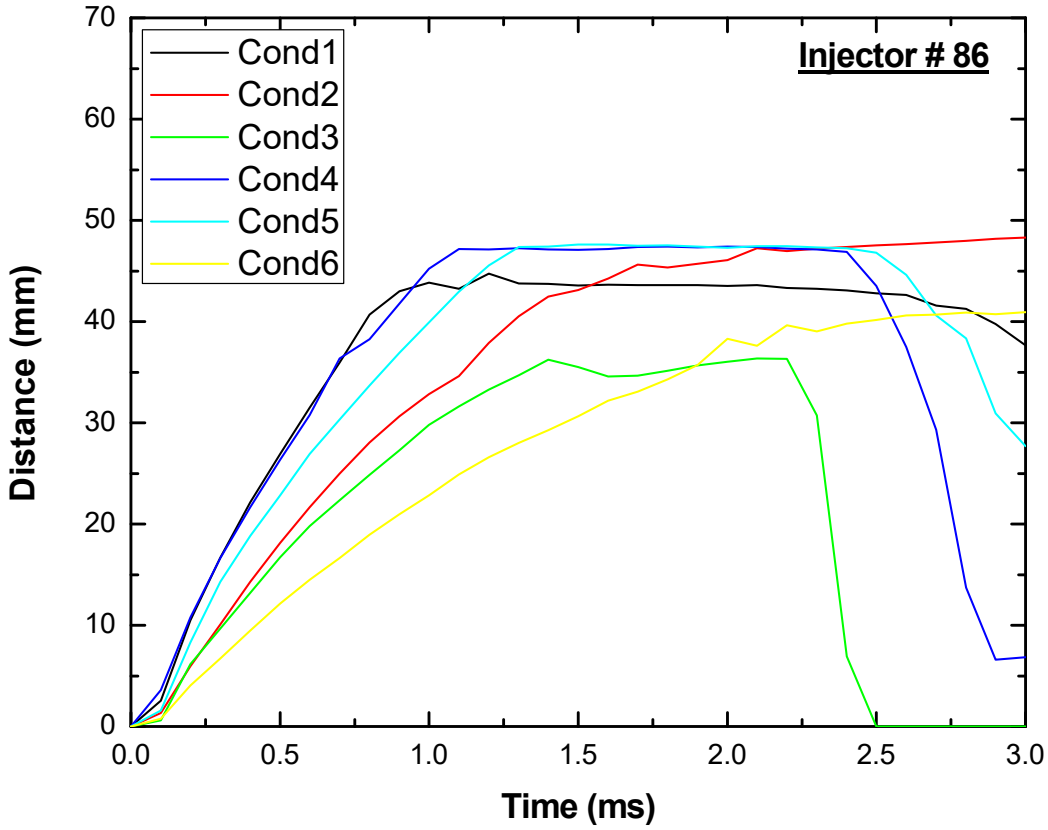
Sample results from X-Ray



- Deconvoluted results of mass fraction of water
- With SPIV, provides mass flux within 5%
- With patternator provides drop size within 20%

SPIV shadowgraphy (penetration velocity)



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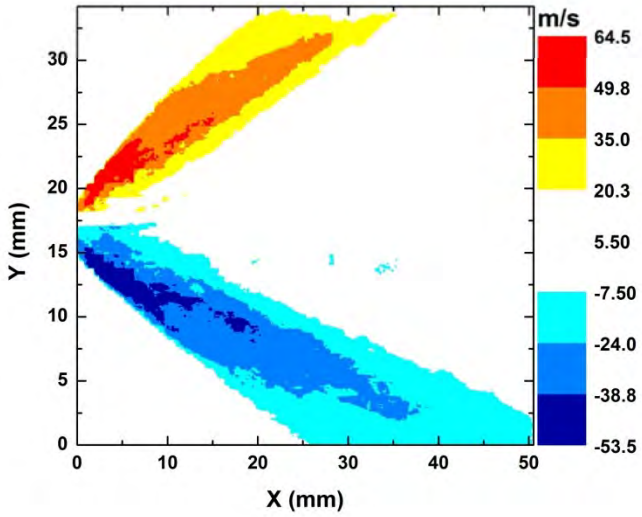
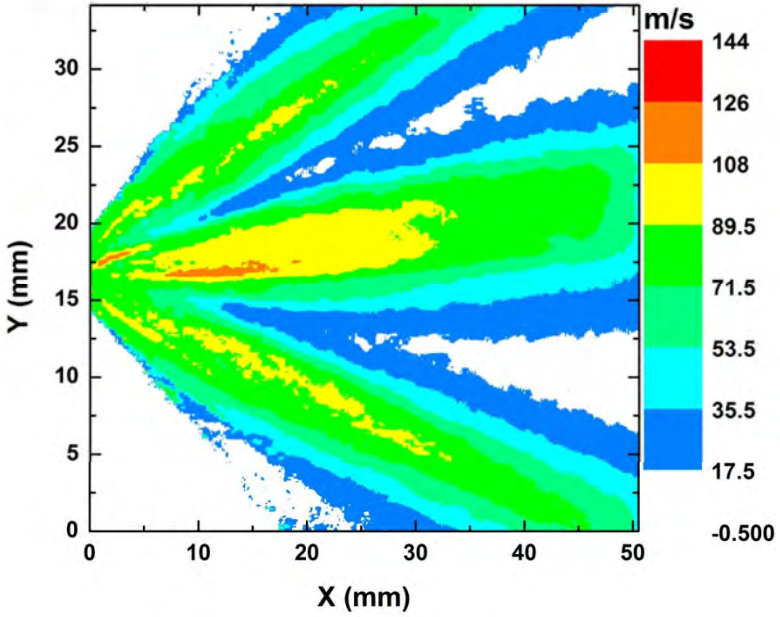
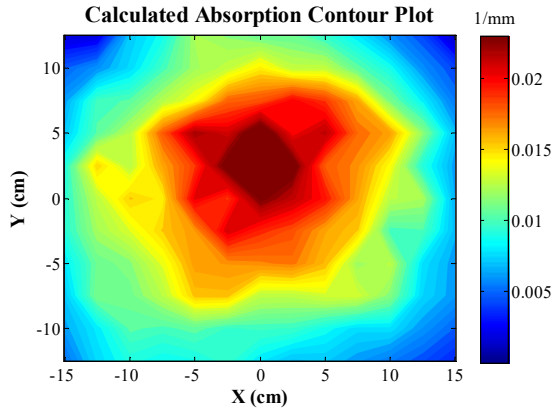
Sample Results SPIV

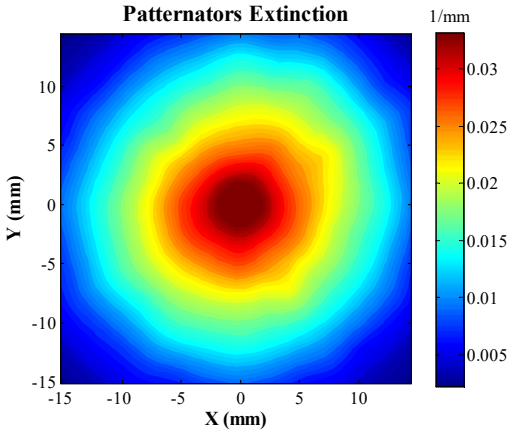


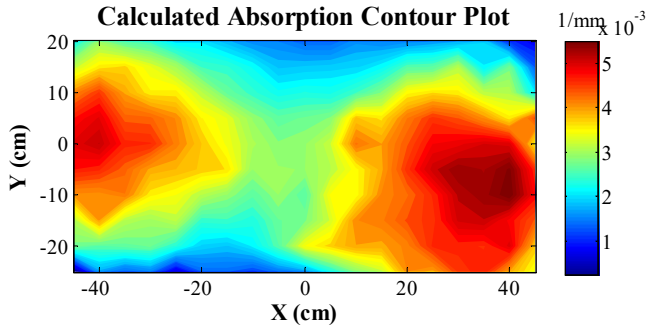


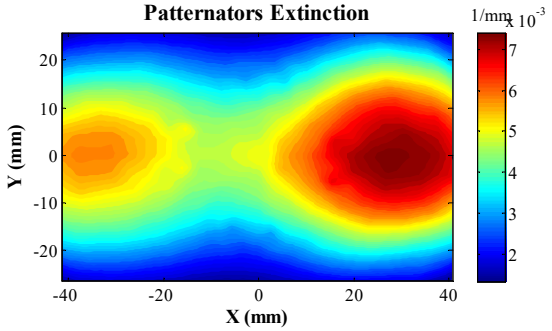
GDI Injector at 20 MPa

PDA vs Patternator









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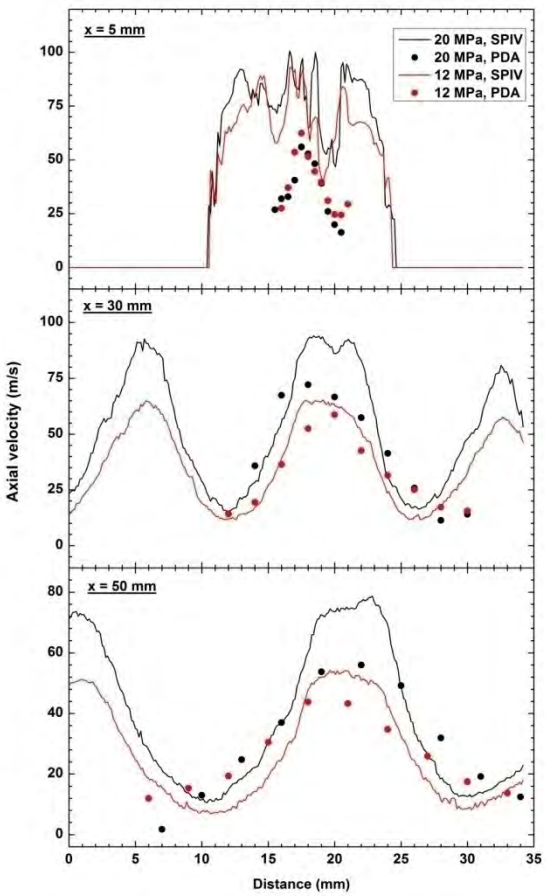
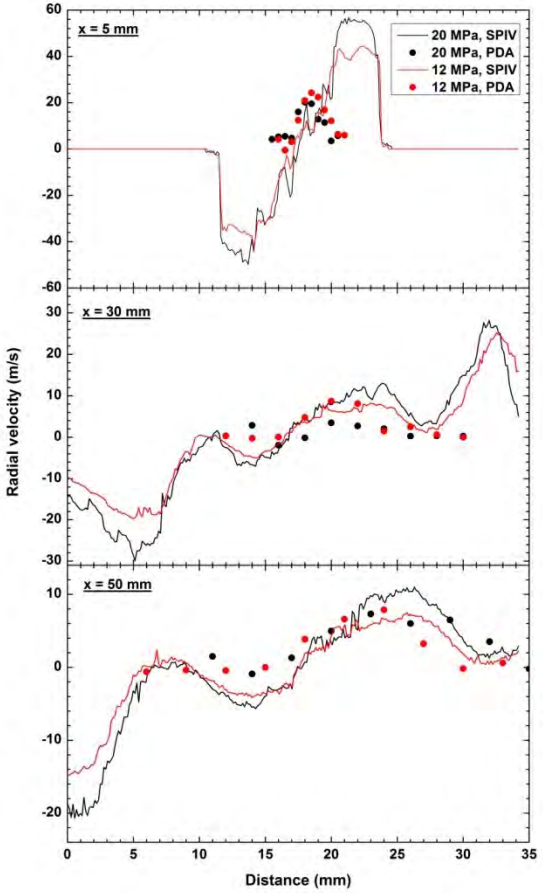
Velocimeter vs PDA





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Spray characterization at En’Urga Inc.

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Current Spray Instruments

Optical patternator

Large area patternator

X-Ray mass flow meter

Pattern Imaging Velocimeter

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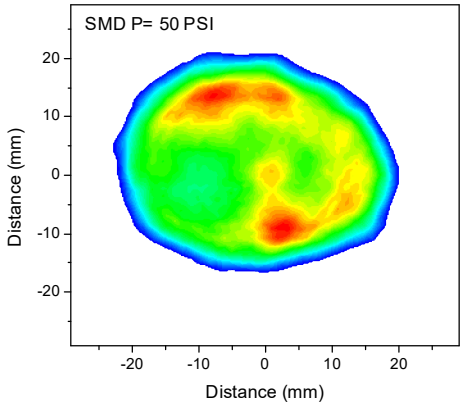
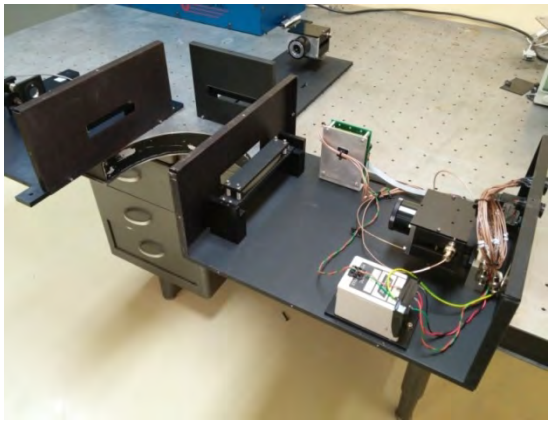
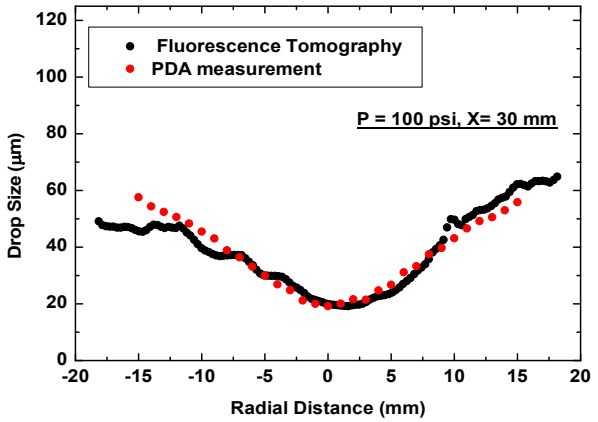
Instruments under development

Planar drop sizer



Fluorescence tomography





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