The quality audit of fuel injectors: Best practices

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Motivation

- Optimization of fuel sprays provide one of the best methods for increased efficiency
- Wide variation in injector performance, even from the same manufacturer
- Current quality audit methods do not pick up even significant differences
- Key question: What can be done to provide for a better quality audit of injectors

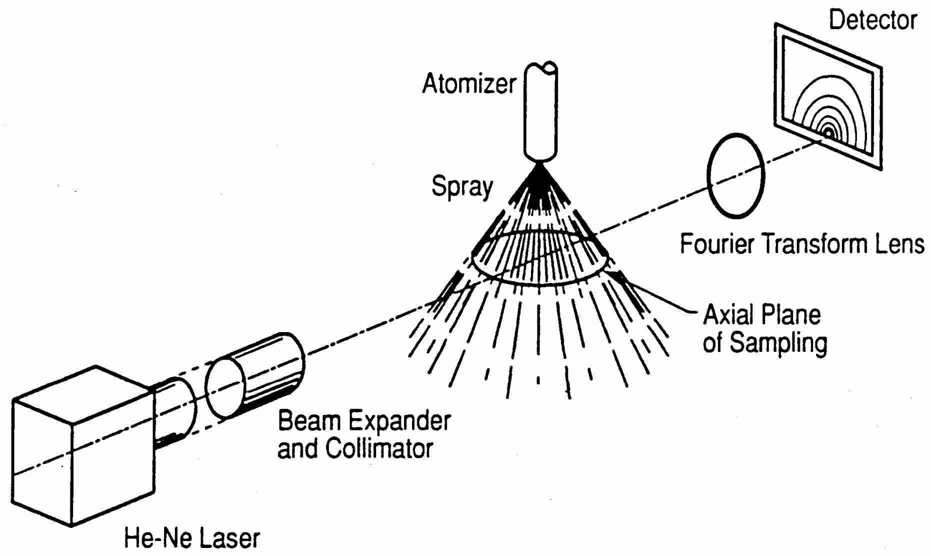
Ranking of Attributes

- Method should be repeatable
- Sensitive to small differences
- Accurately estimate key spray characteristic
- Equipment should be easy to operate

Methods used in Study

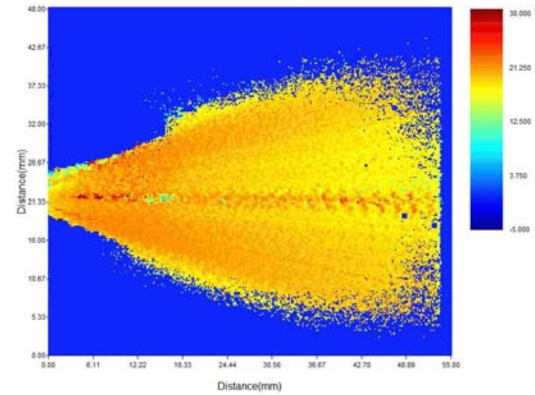
- **Drop sizing using Diffraction**
- **Plume penetration using SCIvel velocimeter**
- **Planar surface area density using SETscan patternator**

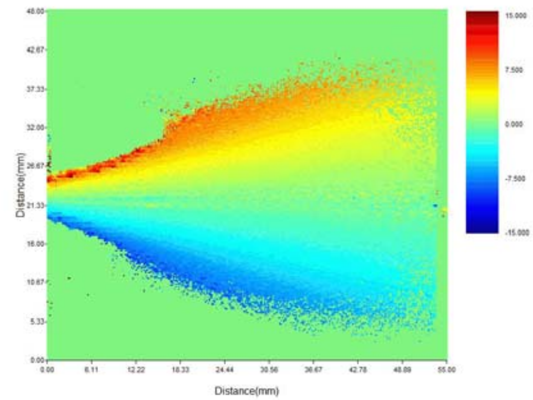
Drop sizing principle



Diffraction signal analyzed to provide transient drop sizes

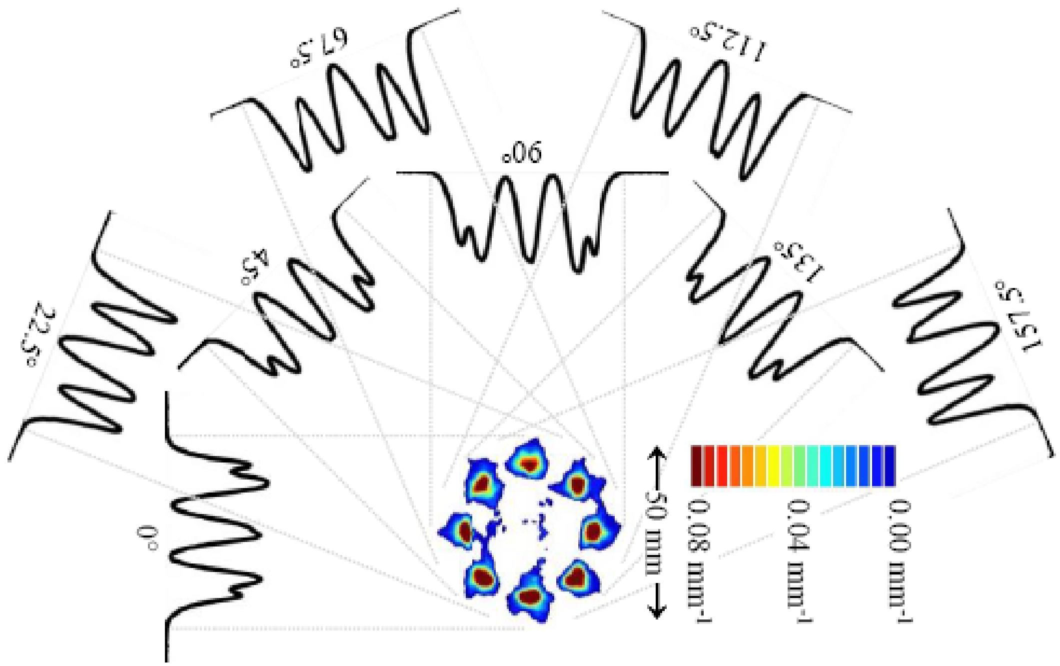
Image Correlation Velocimetry





Transient and steady state X and Y velocities using high speed shadowgraphs

Drop surface areas from Patternator



- **Tomography of extinction data with a sampling frequency of 9.4 KHz**

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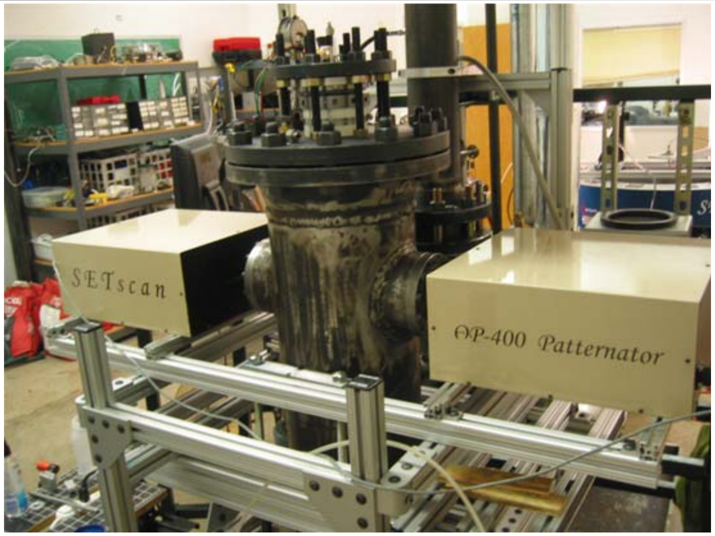
Test Details (GDI injector)

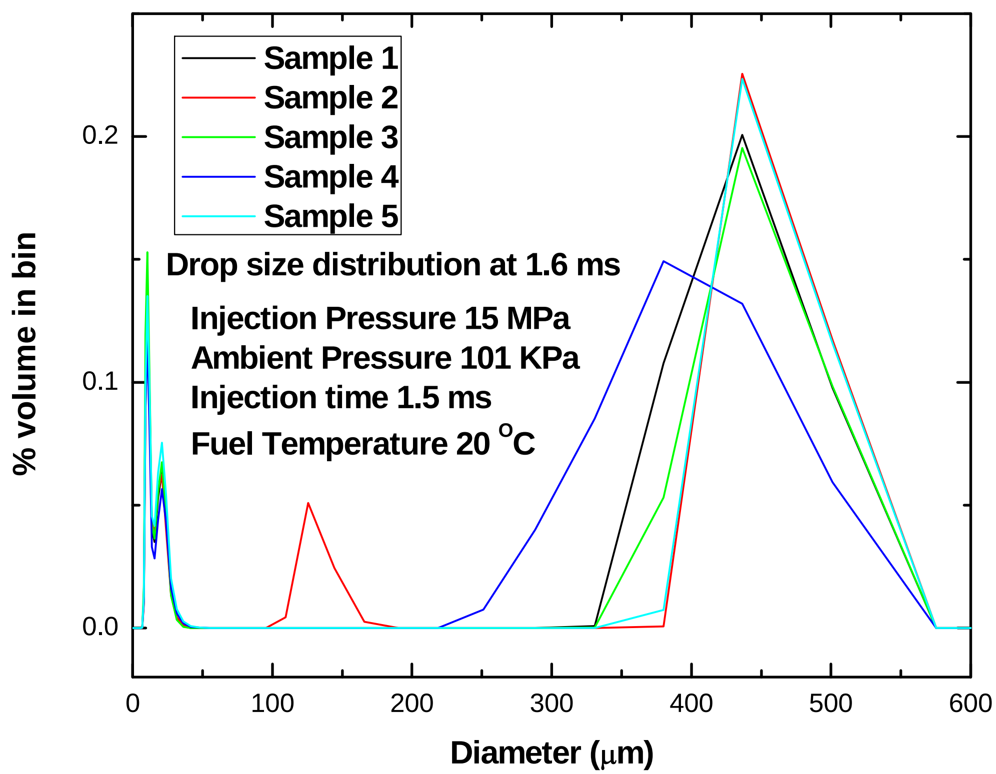


Pressure vessel fitted with AP400 patternator
Maximum field of view is 100 mm

- **Injection pressures: up to 20 MPa**
- **Ambient pressures: 40 Kpa to 1.5 Mpa absolute**
- **Fuel temperature: up to 90 ^{O}C**
- **Fuels: Gasoline or Heptane**

Sample Results

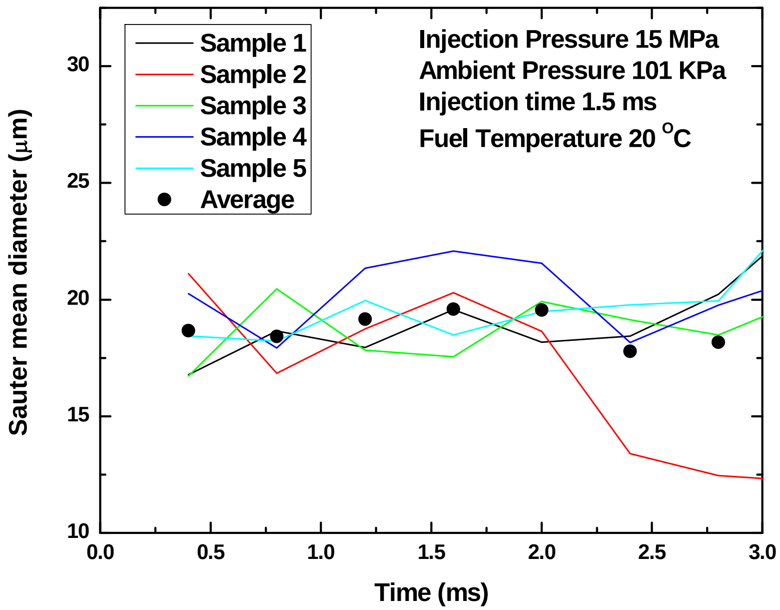
Drop Size Distribution



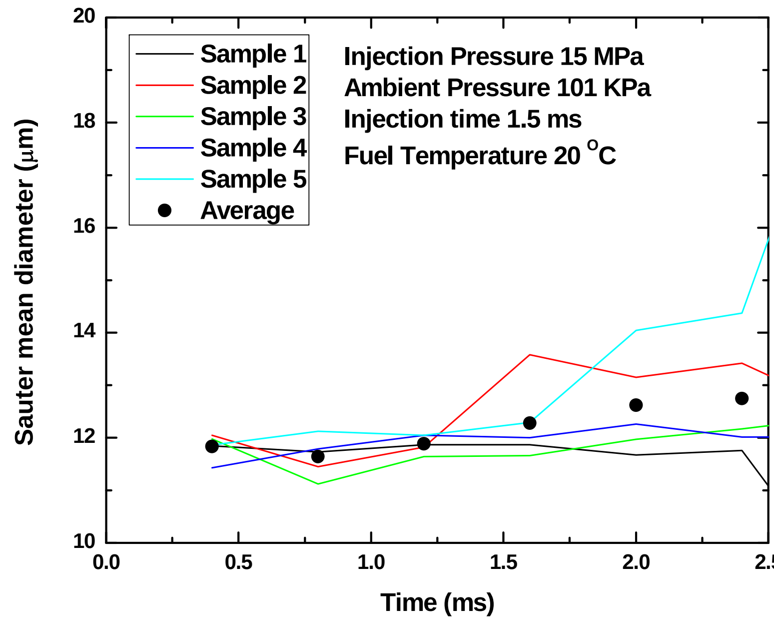
- **Obscuration is very high**
- **Large peak at high values probably caused by beam wandering**
- **Usually bimodal distribution**
- **Measurements obtained through one plume**
- **Results are average across the 10 mm diameter laser beam**

Mean drop diameter (D_{32})

All drops from 0 to 500 microns



All drops from 0 to 200 microns



- Standard deviation in first case is ~ 10%
- Slightly better during initial phase for second case

Difficult to rank injectors and probably not a good quality audit tool

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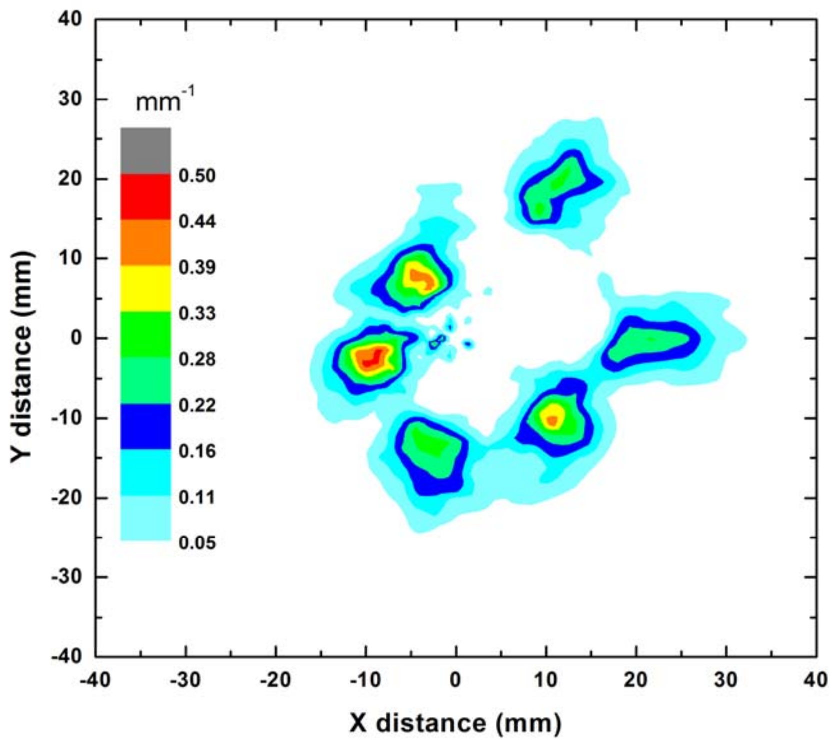
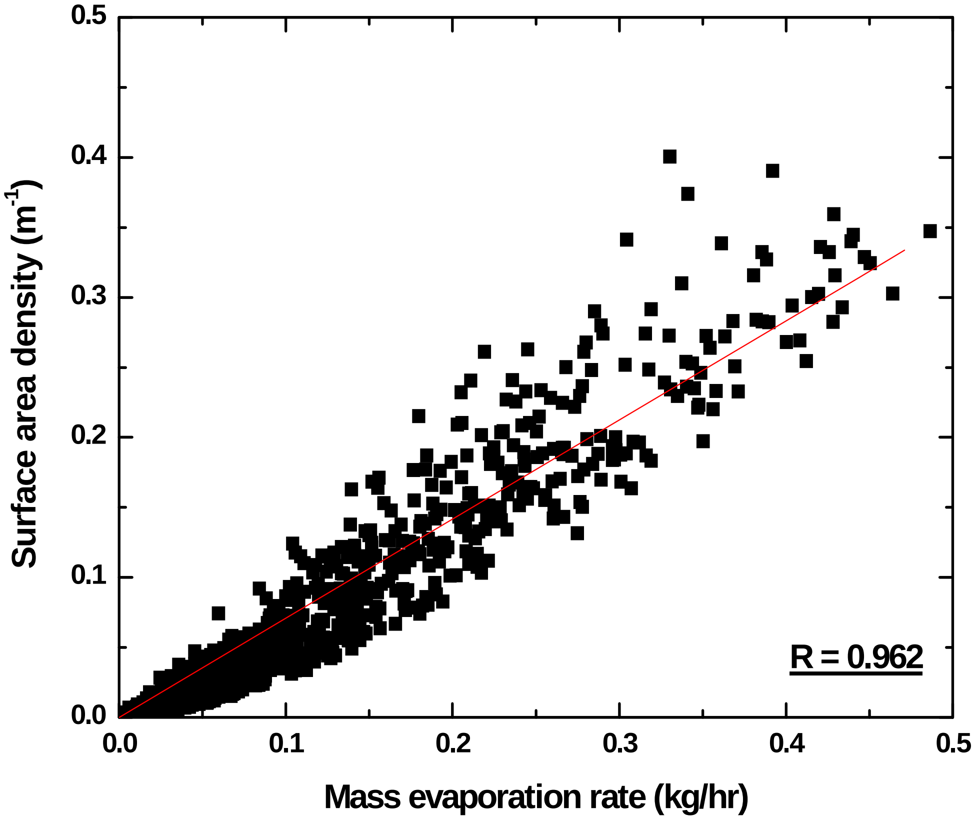
Patternator Results



- 15 bar injection pressure
- Data collection with injection pulse
- Contour maps of surface area density
- Data collected for ~ 2 to 3 ms after injection pulse
- Analysis based on 5 samples
- Results are for the entire plane

Importance of surface areas

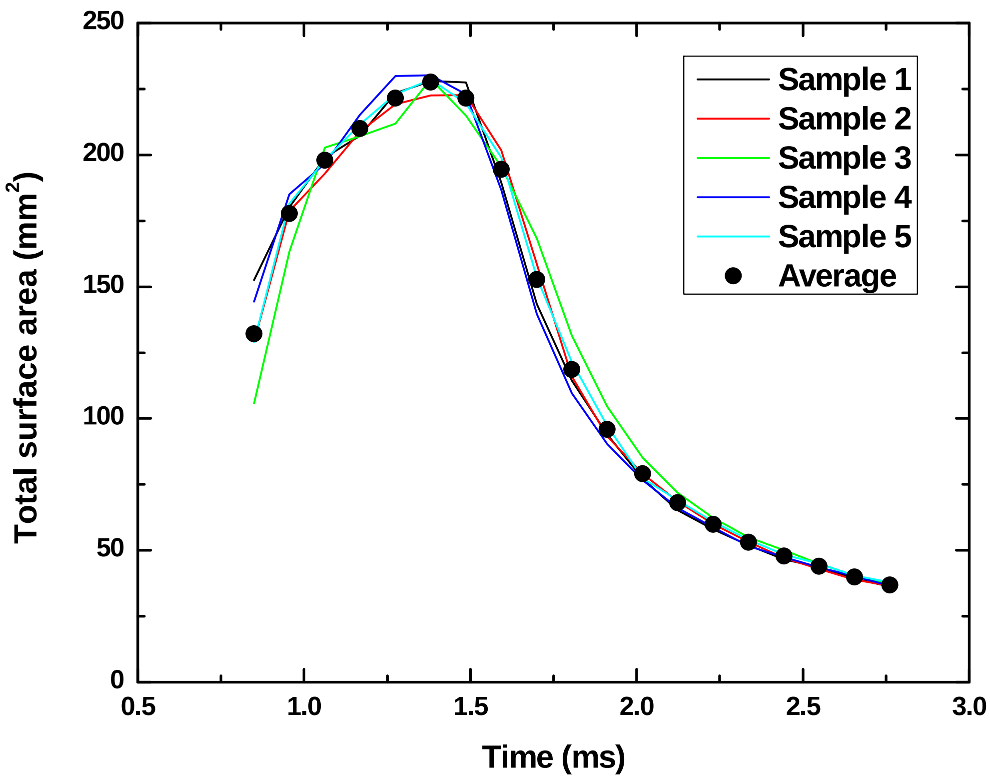
Correlation of fuel evaporation with parameters



Drop size = 0.681
Velocity = - 0.239
Mass flux = 0.903
Surface area density = 0.962

Surface area density is the most important parameter to measure if you are interested in obtaining the amount of fuel evaporated at any location in a spray

Sample Repeatability



- Total surface area is the total surface area of all the drops within a 1 mm height in the patternation plane
- Standard deviation (other than the first instant) is <5%
- If total surface area over entire injection period is taken, standard deviation is less than 0.5%

Ideal variable for ranking and quality audit of different nozzles

Plume Analysis

Mean Plume angles (deg)	Standard Error	% area in plume	Standard Error
10.89	0.13	19.32	0.66
5.73	0.11	4.69	0.14
11.53	0.13	21.71	0.92
10.48	0.37	17.91	0.71
11.51	0.32	23.06	0.24
9.35	0.36	12.93	0.95
Mean centroid (x,mm)	**Standard Error**	**Mean centroid (y, mm)**	**Standard Error**
3.26	0.12	-5.69	0.19
-4.84	0.14	14.3	0.13
22.13	0.25	1.97	0.06
29.04	0.12	10.75	0.09
15.36	0.13	-18.49	0.03
0.10	0.12	-20.01	0.17

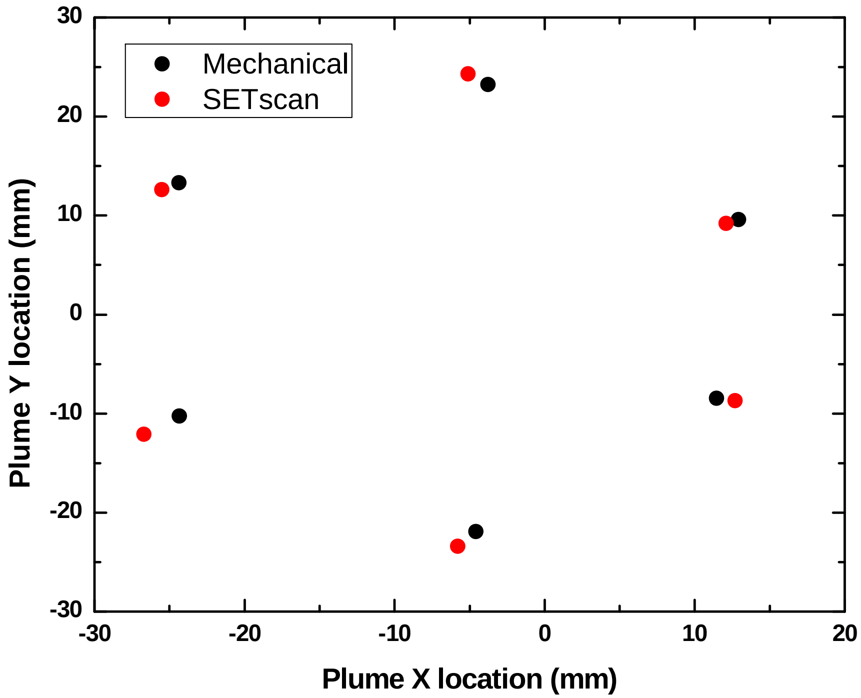
Centroids within 200 microns

Plume angles within 1/2 degree

% distribution in plumes within 1%

Improves with more samples

Comparison with Mechanical Patternator



- Mechanical patternator has stagnation planes
- Requires extensive time and effort
- Spatial resolution not very high for mechanical patternator
- Results show that mass flux centers correlate well with surface area centers

Fully automated plume analysis for quality audit

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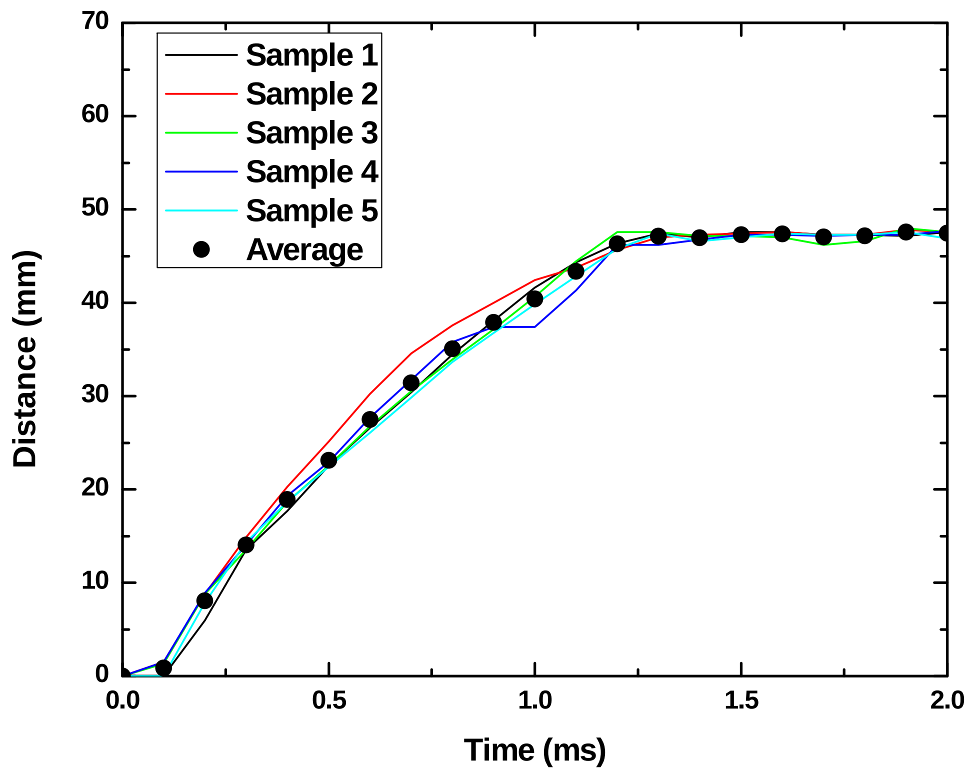
Penetration Distance

- Injection pressure 10 MPa gage, Chamber pressure 40 Kpa absolute
- Fuel temperature 90 ^{O}C
- Plumes overlap

Repeatability of measurement



- Extinction based measurement, similar to the patternator
- Standard deviation in all cases (other than the first sample) is ~ 5%
- Higher than the patternator since whole field image has some errors due to secondary emission

Can be used for quality audit, but not ideal for ranking of nozzles

Case study in design/selection of injector

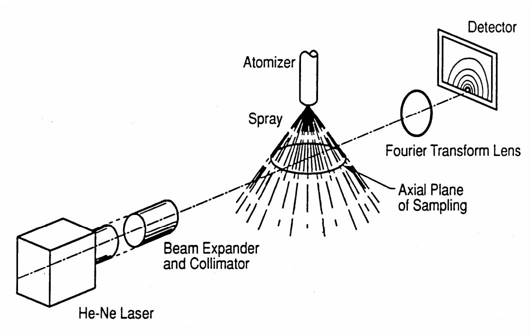
Drop sizes through one plume from 3 injectors:

A: 25.4 +/- 2.5 microns

B: 25.5 +/- 2.5 microns

C: 22.1 +/- 2.2 microns

Difficult to choose which is the best



Drop surface areas across entire plane

A: 193.2 +/- 3.8 mm^2

B: 220.1 +/- 4.4 mm^2

C: 199.6 +/- 4.0 mm^2

Easy to decide which injector provides the best performance

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Conclusions

- There is some variation in the shot to shot characteristics of sprays from fuel injectors
- When testing spray under actual operating conditions within a pressure chamber, it is difficult to have a large sample size
- Diffraction based measurements may not be ideal for ranking nozzles under such conditions
- Extinction based measurements show higher consistency that diffraction or scattering based measurements under real operating conditions
- Planar extinction tomography has been shown to be the best method for ranking nozzles or for quality audit purposes.