“Role of Alternative Aviation Fuels on Reducing the Carbon Footprint”

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Funded by:

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الصندوق القطري لرعاية البحث العلمي
Qatar National Research Fund
Member of Qatar Foundation

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Outline

- Role of alternative aviation fuels
- Introduction
- Collaborative research
- Fuels
- Research at MSTF-TAMUQ
- Takeaways
- Future directions

Aviation Alternative Fuels

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- Need for alternative fuels?
  - Diversification / supply security
  - Reduce environmental impact
- Alternative fuels sources?
  - F-T based synthetic fuels (XTL)
    - X- Coal, Gas, Bio
  - Hydroprocessed Renewable Jet Fuel (HRJ) / Hydroprocessed-Ester / Fatty acids (HEFA) – from vegetable oils / animal fats
    - Camelina, Jatropa, Algae, Tallow, used cooking oil etc.,
  - Direct-Sugar-to-Hydrocarbon
  - Alcohols-to-Jet (ATJ)

Aviation Alternative Fuels

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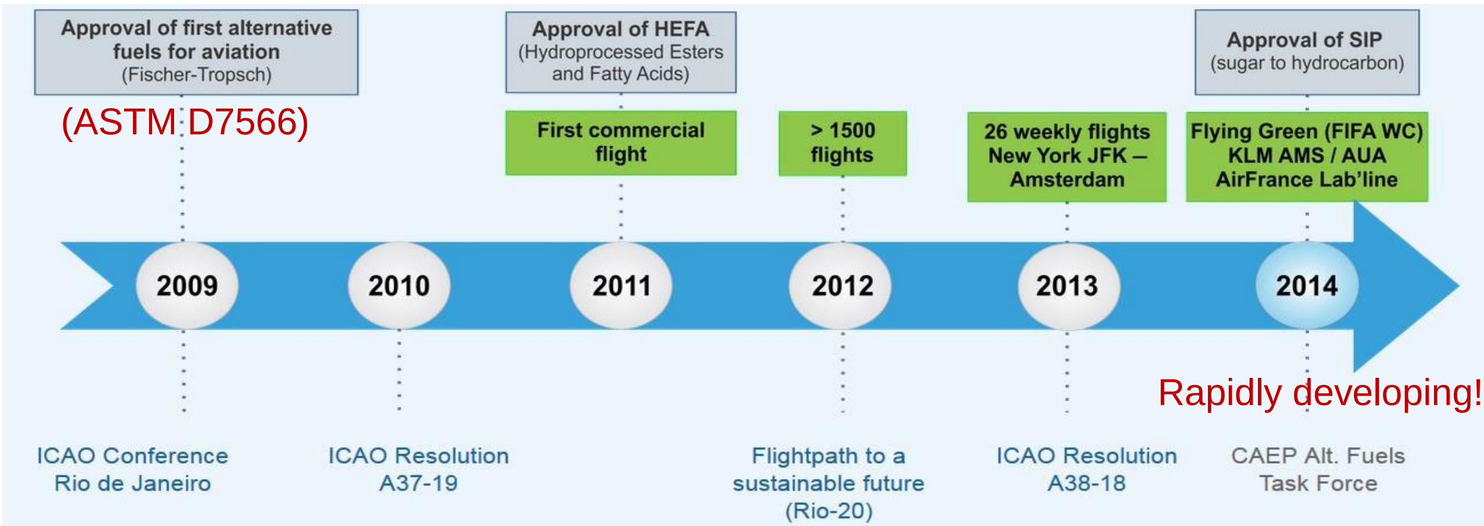
➢ Developments / Milestones?

Source: www.icao.int



"*A total of 21 airlines have now used alternative fuel for commercial flight. This is extremely impressive when just 5 or 6 years ago the entire concept was labeled as hypothetical*." - IATA report on Alternative Fuels, 9th Ed., Dec' 2014

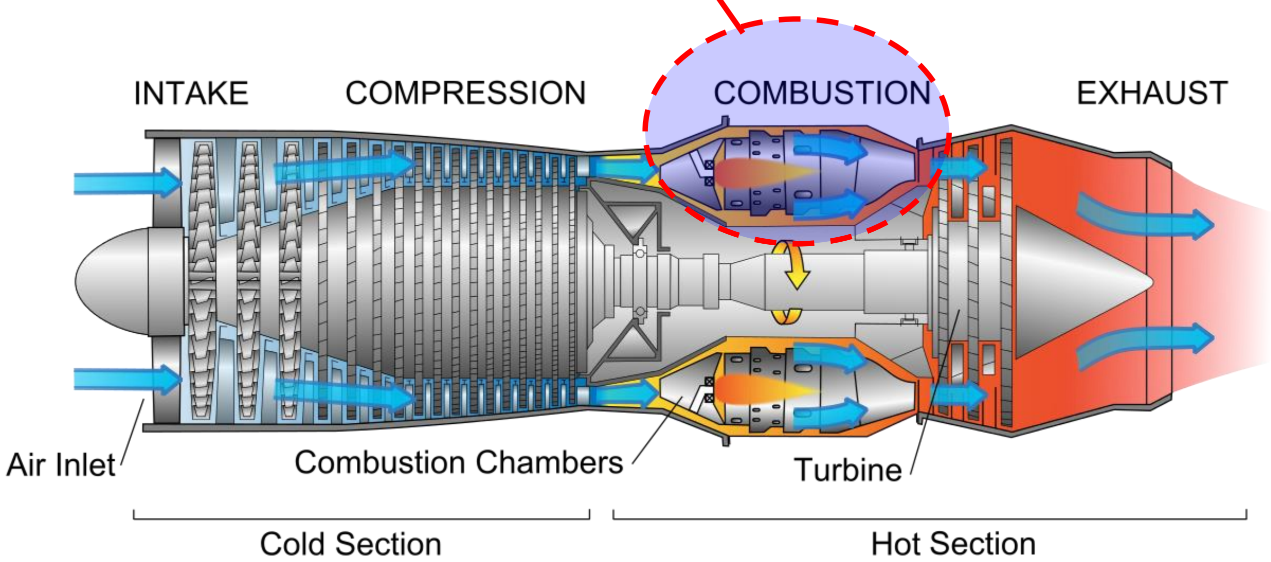
Key challenges in developments?

- Safety & Environmental impact
- Sustainability
- Cost factor
- Land impact
- Food-water security

Safety / Environment?

- New fuel has to meet the performance standards of ASTM
- Chemical and physical properties – different

Combustion ← Fuel-Oxidizer mixing
Chemical → Combustion → Emissions
Physical → Atomization → Fuel-Oxidizer mixing



source: Internet

Introduction / Motivation

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- Abundance of Natural gas in Qatar instigated interest in "Gas-to-Liquid (GTL)" fuel as *drop-in* fuel for aviation engines

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Qatar Science and Technology Park

↓

Academia - Industry Consortium Research

↓

Properties | **Combustion** | Performance

↓

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

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Rolls-Royce

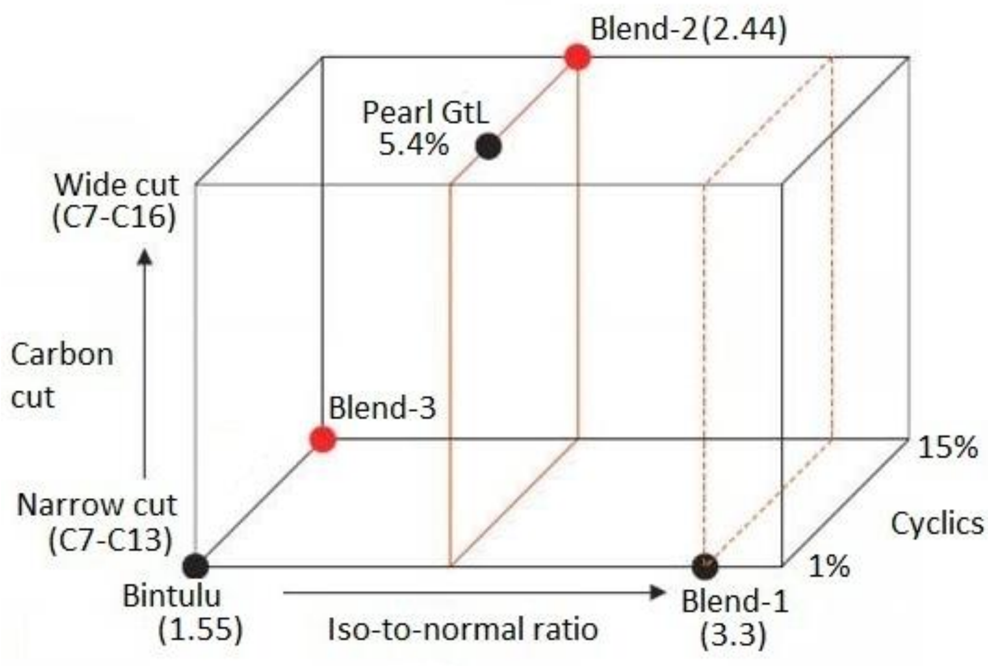
Shell

- *Part-1 : High altitude relight ignition tests at R-R, UK*
- Part-2 : *Emission tests at R-R, USA*
- Part-3 : *Combustion studies at DLR, Germany*
- Part-4 : Atomization study at TAMUQ, Qatar

GTL Fuels : Shell

Gas-To-Liquid (GTL) : liquid fuel synthesized from Natural gas using Fischer-Tropsch

- Effect of fuel composition on combustion;
  - Carbon range
  - Iso-to-normal paraffin ratio
  - Cyclic content



[Bauldreay et al., 2011]

- Five GTL fuels – Shell
  - Two commercial fuels
    - Bintulu GTL - Malaysia
    - Pearl GTL - Qatar
  - Three blends:
    (Bintulu + "*ShellSol*")
- Reference fuel: Conventional "Jet A-1"

Fuel properties: Shell

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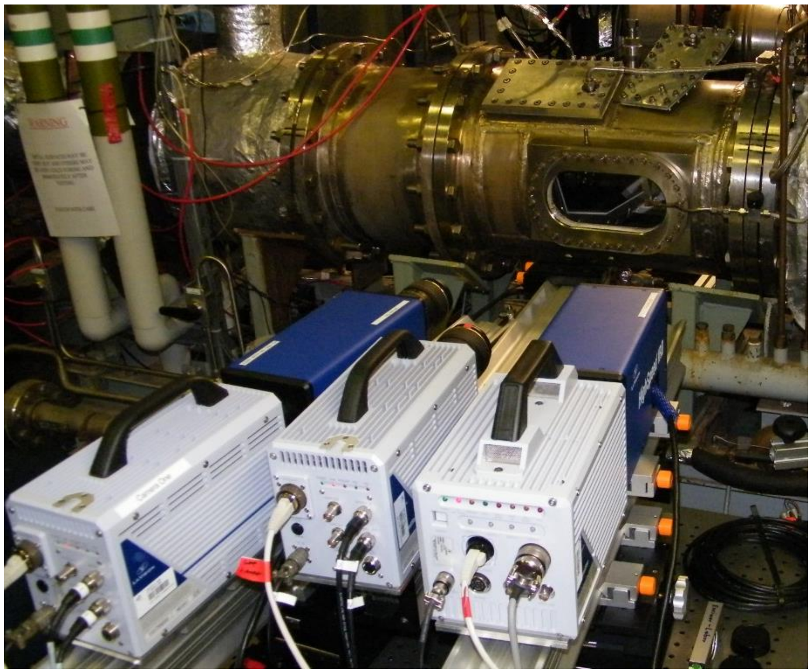
Properties @ 20°C	Blend-1	Bintulu (CSPK 1)	Blend-3	Blend-2	Pearl (CSPK 2)	Jet A-1
Density (kg/m^3)	746	738	751	763	749	790
Viscosity (mm^2/s)	1.36	1.37	1.46	1.60	1.55	1.68
Surface tension (mN/m)	23.8	23.5	24.1	24.2	23.9	26.8
H/C ratio (measured)	2.2	2.3	2.2	2.2	2.2	1.92
Iso-paraffins (% Wt)	73.3	55.7	48.4	58.1	64.8	NA
Normal paraffins (% Wt)	26.0	43.4	36.5	26.7	29.8	NA
Iso-to-normal paraffin ratio	3.3	1.6	1.5	2.4	2.5	NA
Naphthenes (% Wt)	0.4	0.5	15.4	15.6	5.4	NA
Carbon Cut Narrow (C7-C13) / Wide (C7-C16)	Narrow	Narrow	Narrow	Wide	Wide	NA
Distillation Characteristics (°C)						
T50 - T10	8.4	16.6	8.4	10	9.4	28.5
T90 - T10	20.7	22.5	21.2	27.5	28.7	68.3

- Calorific value (LHV as per D4809 standard) : 43.3 ~ 44.2 MJ/kg

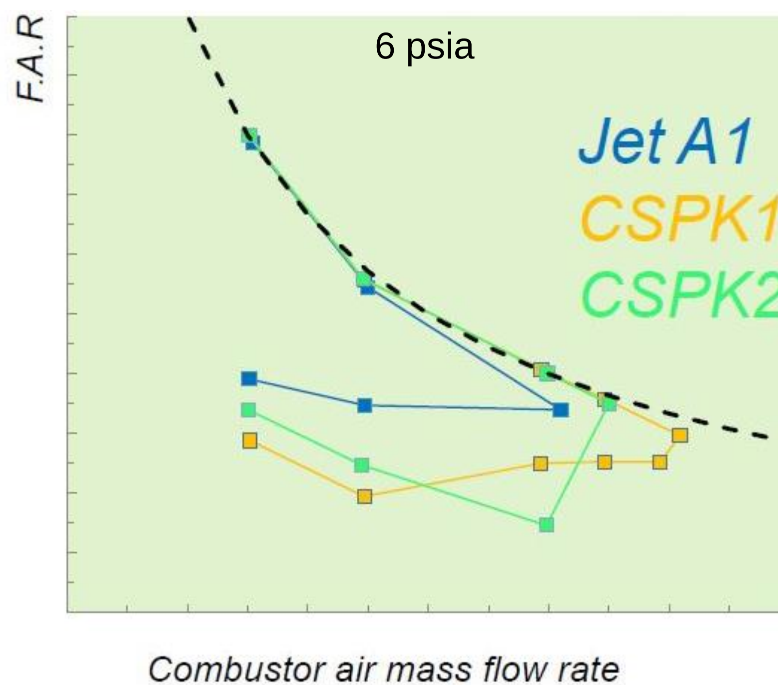
Part-1: Relight Ignition

(RR-UK, DLR-Germany, TAMUQ-Qatar)

- High altitude relight ignition tests
- Sub-atmospheric combustion rig – Rolls-Royce, Derby-UK
- Limits of ignition boundary tested at two combustion inlet air pressures



(Rolls-Royce-UK facility equipped with DLR diagnostics)



Proceedings of ASME Turbo Expo 2011: Power for Land, Sea and Air, June 6-10, 2011, Vancouver, Canada:

- Darren et al., (2011), GT2011-45487
- Thomas et al., (2011), GT2011-45510

Part-2: Emission Tests

(RR-UK, RR-US, TAMUQ-Qatar)

- Emission characteristics : NO_x, CO, CO_2, UHC, and smoke number
- IP - Combustion chamber facility at RR-Indianapolis, USA
- Test conditions - represent different stages of aircraft engine cycle – ICAO standards
- Both Main & pilot-scale nozzles were used in emission tests

Emission Tests Outcome:

- At a given combustor operating condition, GTL produced less smoke than Jet A-1
- Under some cases, GTL produced more NOx than Jet A-1 fuel
- Further studies are necessary to gain more insights

Part-3: Combustion studies

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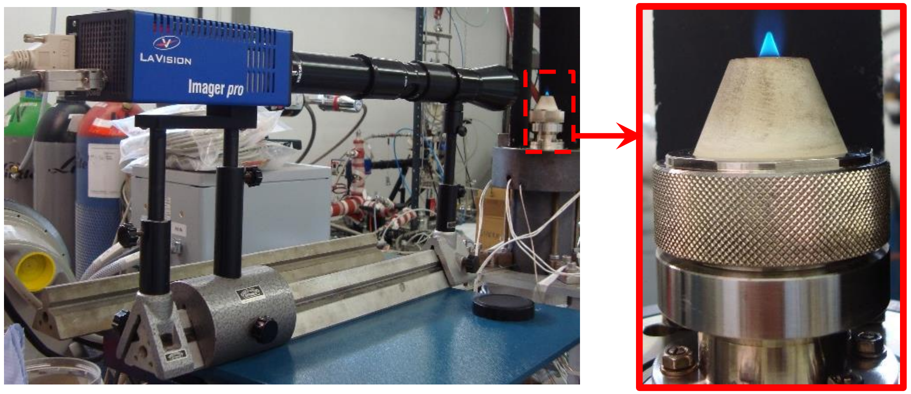
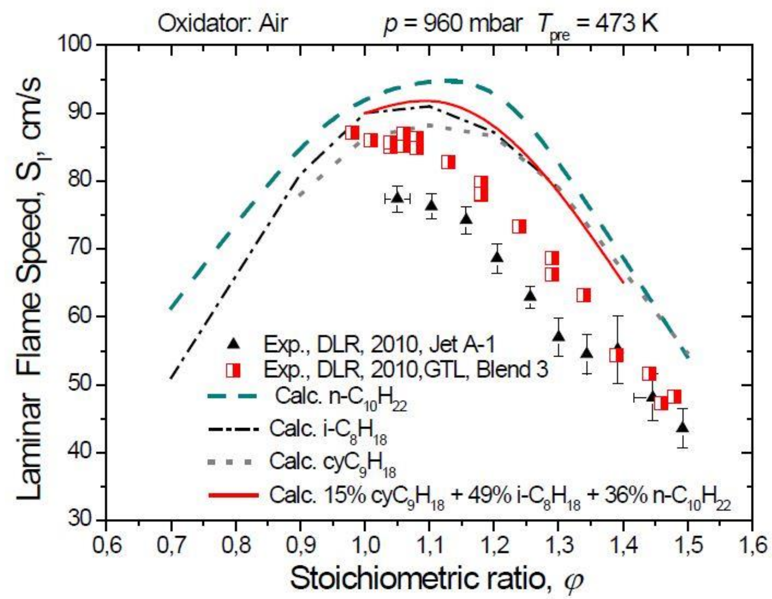
(DLR-Germany, TAMUQ-Qatar)

- Laminar flame speed measurements at atmospheric conditions



(Atmospheric-Laminar flame speed facility, DLR)



- Ignition delay measurements: Shock tube
- Surrogate chemical kinetics – GTL fuel

- Kick et al., Energy 43 (1), 111-123, 2012
- Slavinskaya et al., "Surrogate Model Design for GTL Kerosene", ***50th AIAA Aerospace Sciences Meeting and Exhibit***, Tennessee, USA, 9-12 Jan, AIAA-2012-0977.

Need for spray characteristics?

- Change in physical properties, viscosity, density and surface tension affects the fuel "atomization" characteristics
- Atomization → fuel-air mixture → **Combustion** → **Emissions**

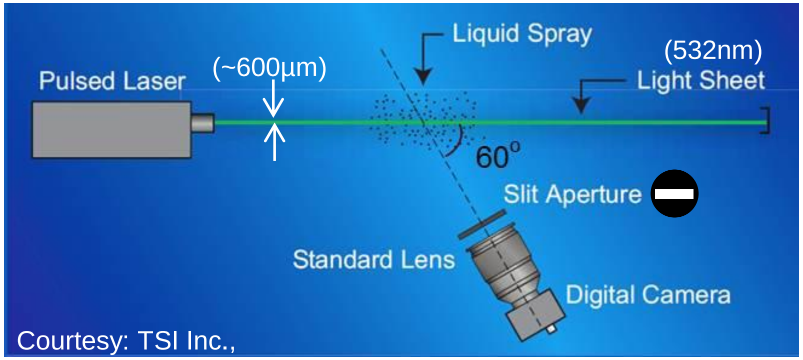
"*Microscopic*" spray characteristics: Droplet size and velocity distribution (GTL vs Jet A-1)

↓

Optical Diagnostic techniques

Plane-wise (Global)	Point-wise (Local)
(*Global Sizing Velocimetry, GSV*)	(*Phase Doppler Anemometry, PDA*)
TSI Inc., USA	Dantec Dynamics, Denmark

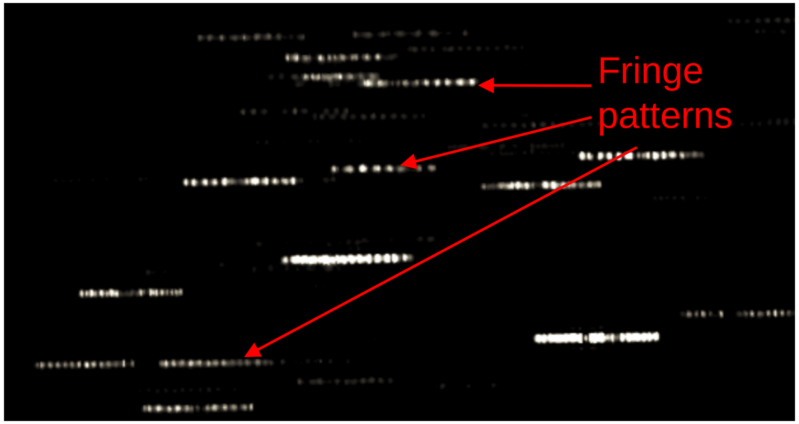
GSV Technique



Lorenz-Mie scattering theory

Out-of-focus image (Ragucci et al. 1990)

Flow ↓ direction



- Fringe spacing is most *"insensitive"* to refractive index at 60° (Pan et al. 2005)
- Light scattered by the droplets exhibit angular oscillations (fringes)
- Droplet size is proportional to the fringe spacing (Pan et al. 2005)

Droplet size measurement limits*

27μm < d < 2mm

** Limits vary with,*

- camera resolution, defocus distance, Magnification, Aperture size

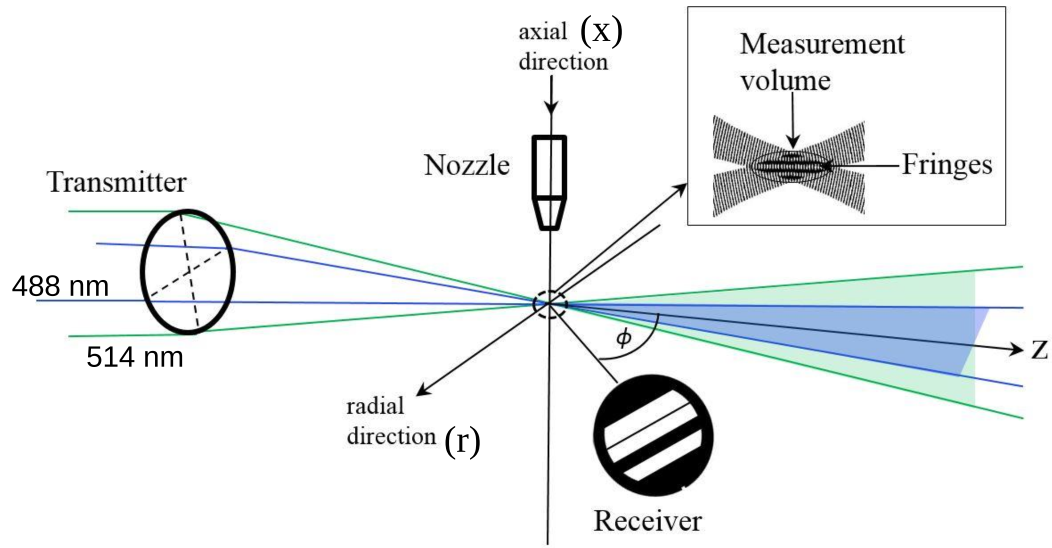
Imaging details

- 200 image pairs (2Hz frame rate)
- 1600x1200/ binning (2x2)
- defocus distance: 135 mm
- Aperture number: 4

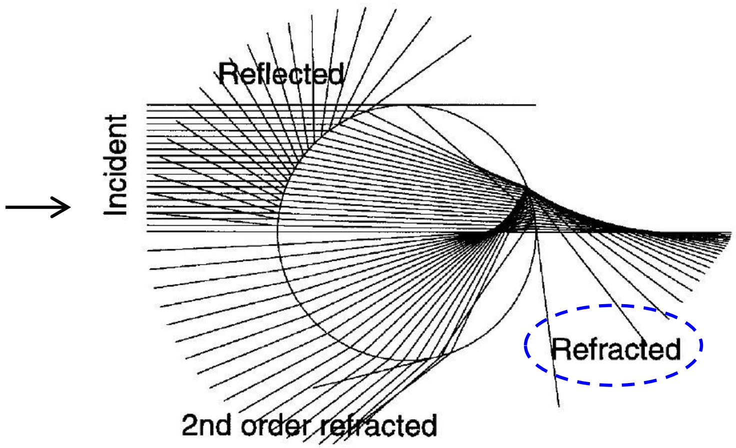
PDA Technique

- 2-D PDA system
- λ = 514nm (axial) and
  488nm (radial)
  - Diameter – Doppler burst phase shift
  - Velocity – Doppler burst frequency

Lorenz-Mie scattering theory



Transmitter and receiver probe arrangement



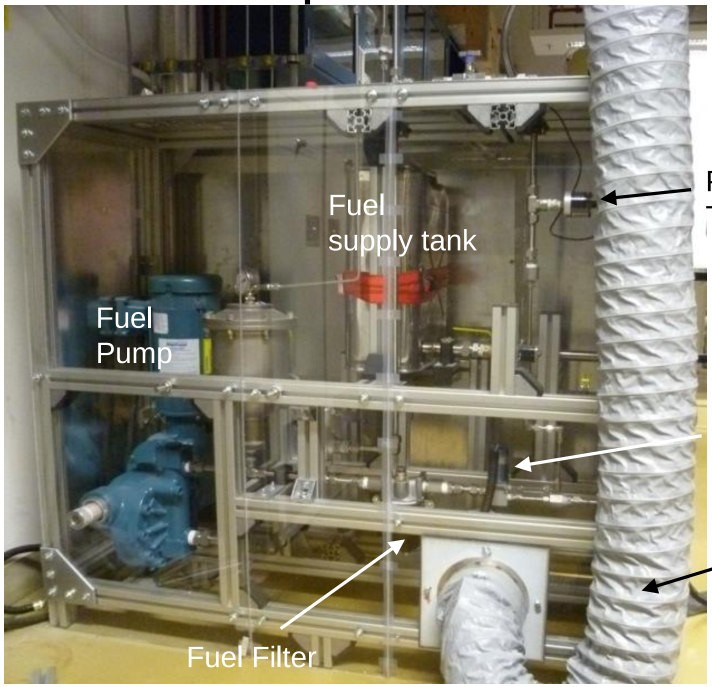
Courtesy: Dantec Dynamics

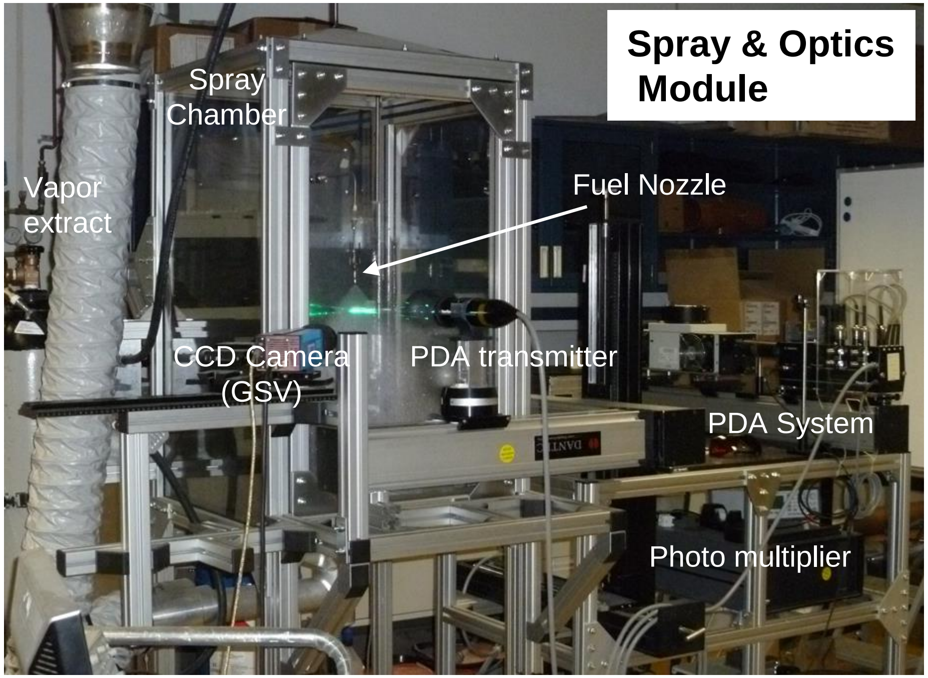
- Receiver probe is positioned at 42^o (φ)
- Data sampling: 10,000 samples or 15s
- Results presented are an average of three best trials
- Validation: Diameter (60-80%)
  Velocity (80-90%)

Experimental Facility

- Three modules – Pump, Spray and Optics
- High pressure fuel supply loop
- Nozzle supplied by RR-UK is mounted on a traversing system
- Injection pressure is measured just upstream of the nozzle
- GSV & PDA systems are integrated to the facility

Pump Module



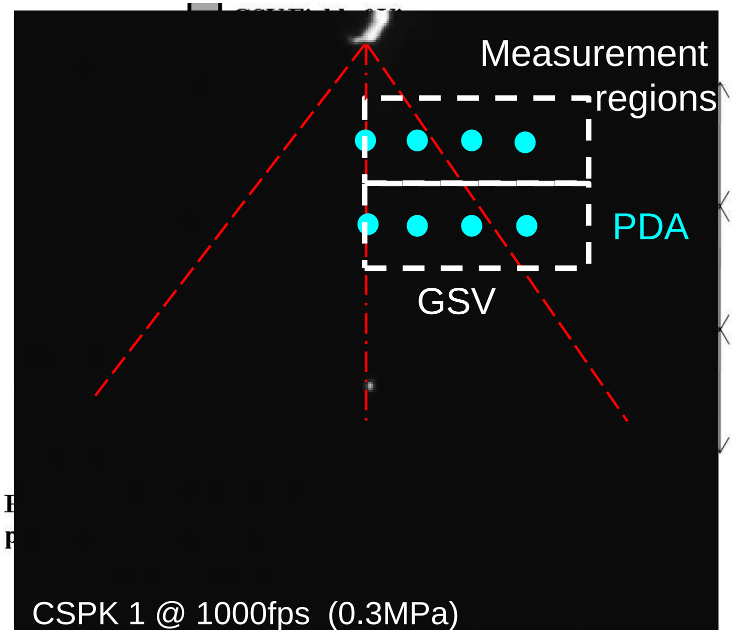


Experiment Details

- Inert (N_2) ambiance at atmospheric condition (101325Pa and 298K)

- Pilot-scale pressure-swirl nozzle: Fuel injection pressures are 0.3, 0.6, and 0.9 MPa (SD ±3%)

- Injection pressures are chosen based on RR-UK suggestions



Schematic of measurement regions

- Spray is symmetric and measurements are carried out only on one side of the spray

- The field of view for GSV is decided based on the facility dimensions, camera lens capability. Radial direction is covered in two steps

GSV: Size Distribution at NS1

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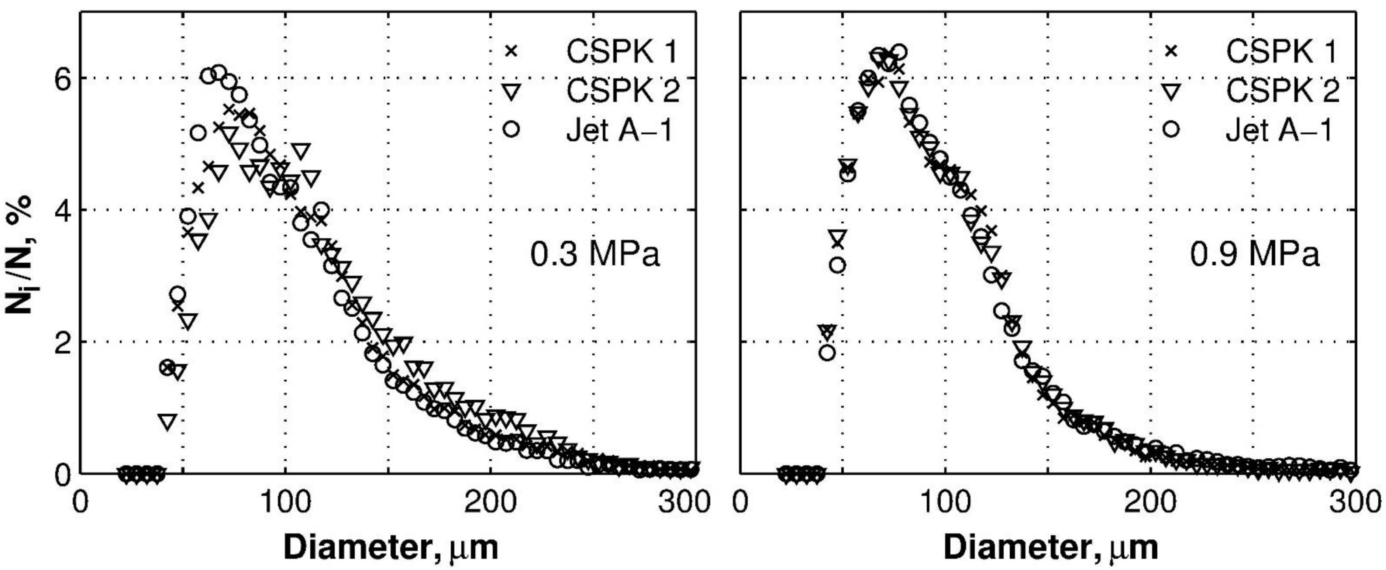
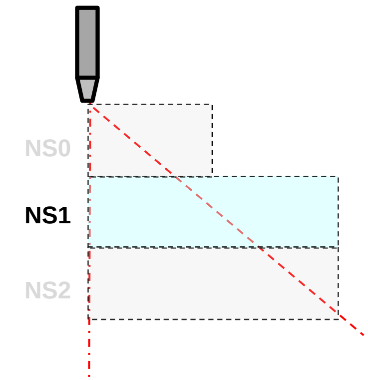
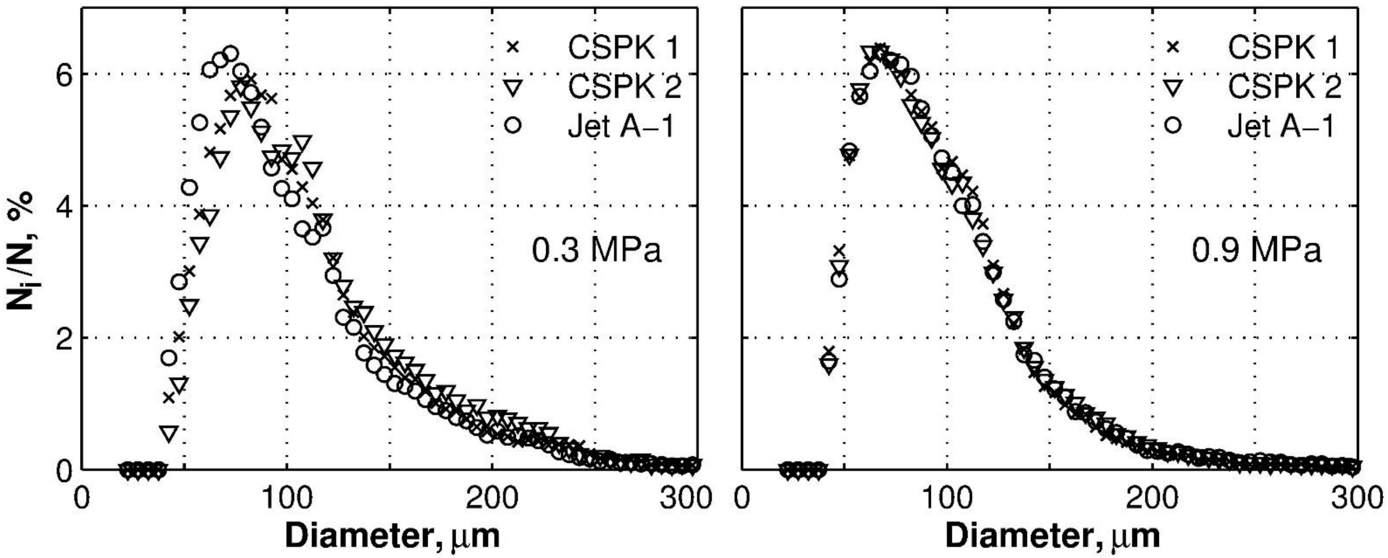


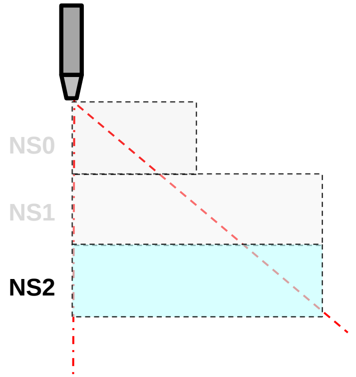


- The difference in size distribution beyond 300 μm is insignificant among the fuels and not shown
- However, full diameter range is used to calculate Sauter Mean Diameter (SMD)
- Increase in injection pressure slightly increases the number of smaller droplets as expected
- Distribution trends are similar

[Kumaran & Sadr, *ICLASS*, 2012]
[Kumaran & Sadr, *Atomization and Sprays*, 24 (7), 575-597, 2014]

GSV: Size Distribution at NS2





- Size distributions trends at NS2 are similar to that in NS1
- The probability is slightly higher at NS2 than NS1

- Mean droplet diameters (d_{10} and d_{32}) decrease with an increase in injection pressure as expected
- The mean diameter trends are consistent with those of the size distributions

[Kumaran & Sadr, *ICLASS*, 2012]
[Kumaran & Sadr, *Atomization and Sprays*, 24 (7), 575-597, 2014]

PDA Measurement Points

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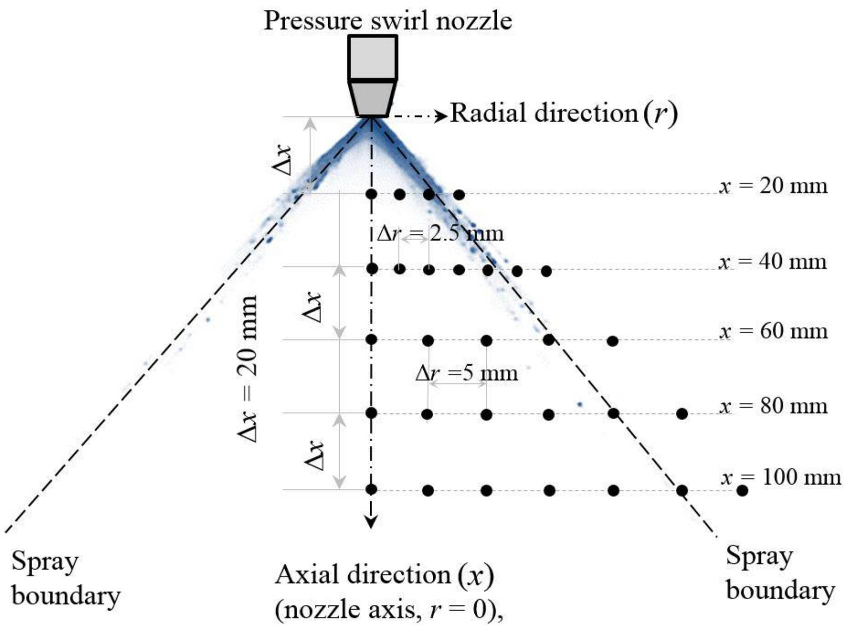
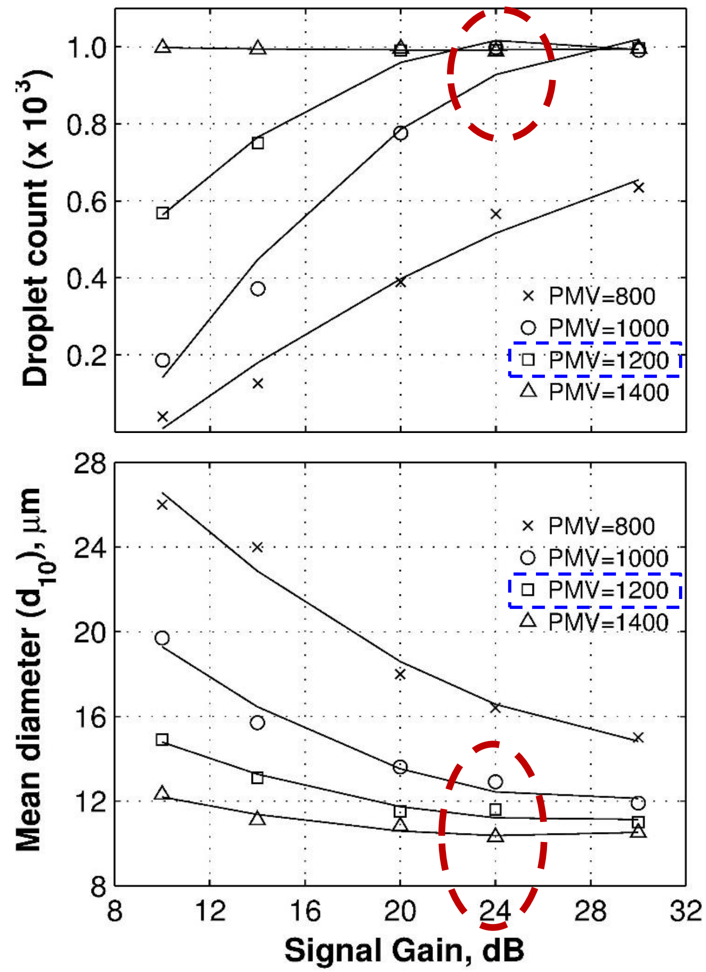
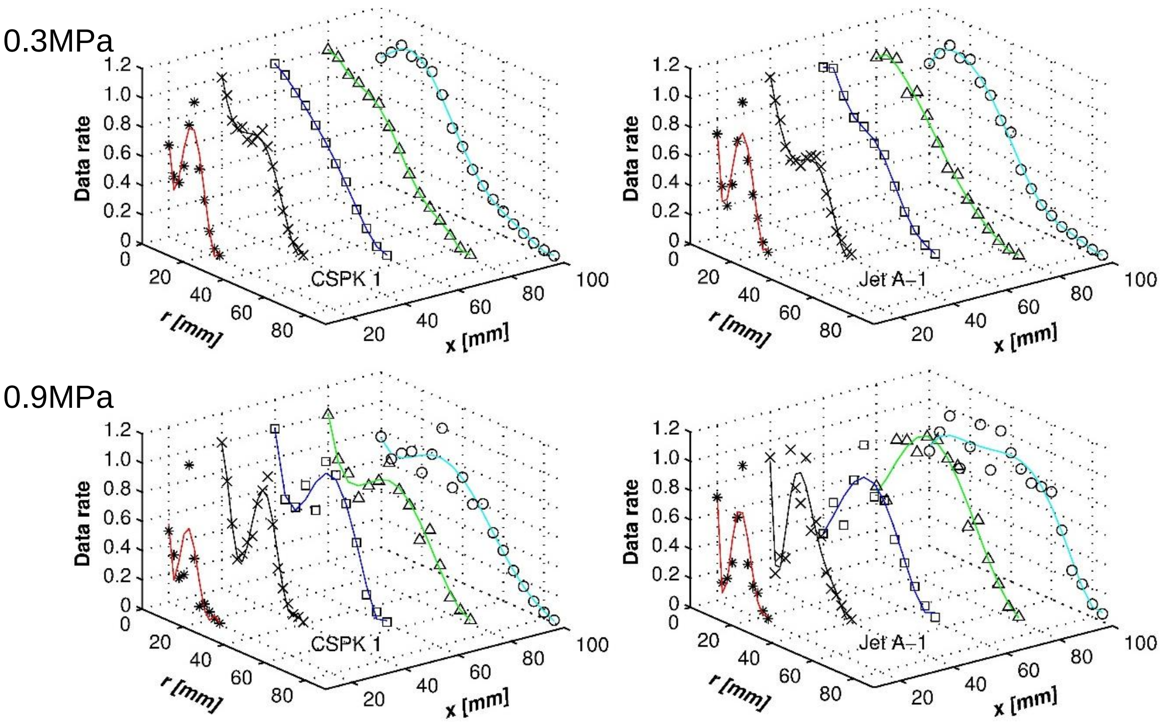


Operating Parameters	
Transmitting optics	
Focal length	400 mm
Beam spacing	38 mm
Beam waist	1.35 mm
Receiving optics	
Focal length	500 mm
Scattering angle	42 º
Aperture mask	Mask-B
Measurement volume	
Diameter (dx)	189 µm
Length (dz)	3.97 mm
Fringe spacing	5.27 µm
No. of Fringes	36



User Settings	
Photomultiplier Voltage (PMV)	1200 V
Signal Gain (SG)	24 dB
Signal-to-Noise ratio (SNR)	-2.0 dB

Normalized Data Rate



Only CSPK 1 & Jet A-1 are shown as they show maximum difference in their fuel properties

- Data rate at last measurement location is less than 3% of the maximum value at that axial location
- Lower values of viscosity and surface tension for CSPK 1: faster disintegration and dispersion of droplets when compared to that in Jet A-1 fuel

Sauter Mean Diameter (d_{32})

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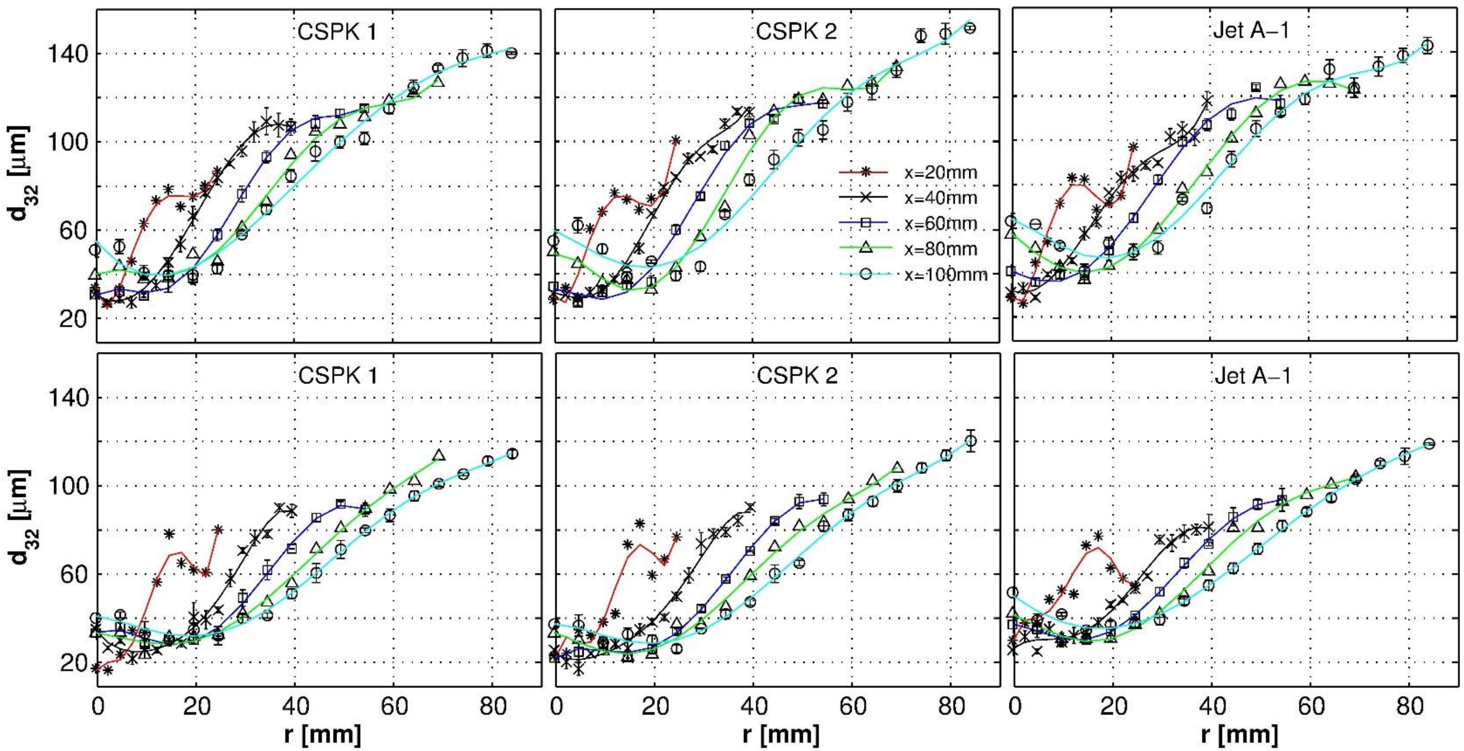
$d_{32} = d^3 / d^2$



0.3MPa

0.9MPa

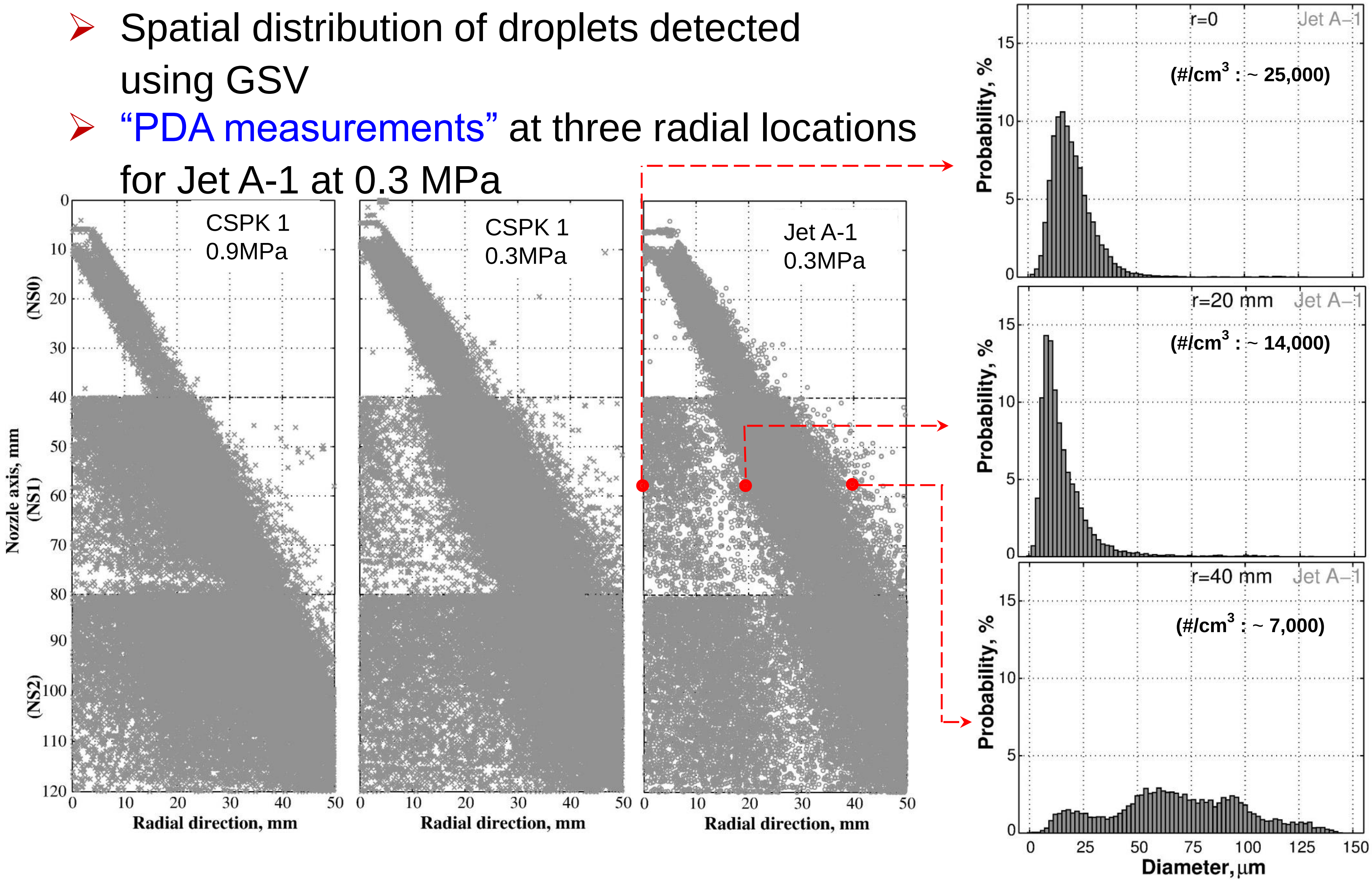
- SMD increases with increase in radial distance for all the fuels as expected in a pressure-swirl nozzle

- CSPK 2 and Jet A-1 trends are similar as their fuel properties are narrowly separated

[Kumaran & Sadr, *Ener.Conv.Mang.*, 88, 1060-1069, 2014]

Spatial distribution

- Spatial distribution of droplets detected using GSV
- "PDA measurements" at three radial locations for Jet A-1 at 0.3 MPa



Takeaways

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GTL vs Jet A-1

- ✓ Better ignition limits at high altitude conditions
- ✓ Better smoke performance

More NO_x emissions than Jet A-1

- ✓ Laminar flame speeds are slightly higher
- ✓ Overall spray characteristics are similar at atmospheric conditions

- Essential to study spray characteristics at actual combustor conditions

Future directions

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Spray Characteristics

→ @ elevated ambient conditions

- TAMUQ / NEU / GE-QSTP (**NPRP-7-1499-2-523**)

→ Role of fuel additives

- Currently in progress

--→ Other alternative fuels

↓ *Mixing / Combustion aspects*

Only a drop in the ocean…

every drop counts**!** ☺

Acknowledgement

- **Rolls Royce, UK**
  - Mr. John Moran, Combustion Specialist
- **DLR, Germany team**
  - Dr. Patrick LeClercq
  - Dr. Thomas Mosbach
- **Shell (UK & Qatar) team**
  - Dr. Joanna Bauldreay, (UK)
  - Mr. Ali M. Al-Sharshani, (QSRTC)

- *late* Prof. Chris Wilson, University of Sheffield
- Dr. Mahesh Panchagnula, Indian Institute of Technology Madras (IITM)

Thank You!

References

- J. M. Bauldreay, P. F Bogers and A. Al-Sharshani, (2011) “Use of surrogate blends to explore combustion-composition links for synthetic paraffinic kerosines”, 12th International conference on stability, handling and use of liquid fuels, Florida, 16-20 October.

- Kumaran Kannaiyan and Reza Sadr, (2014) “Experimental investigation of spray characteristics of alternative aviation fuels”, ***Energy Conversion and Management***, 88, pp. 1060-1069.

- Kumaran Kannaiyan and Reza Sadr, (2014) “Effect of fuel properties on spray characteristics of alternative jet fuels using Global Sizing Velocimetry”, ***Atomization and Sprays***, 24 (7), pp. 575-597.

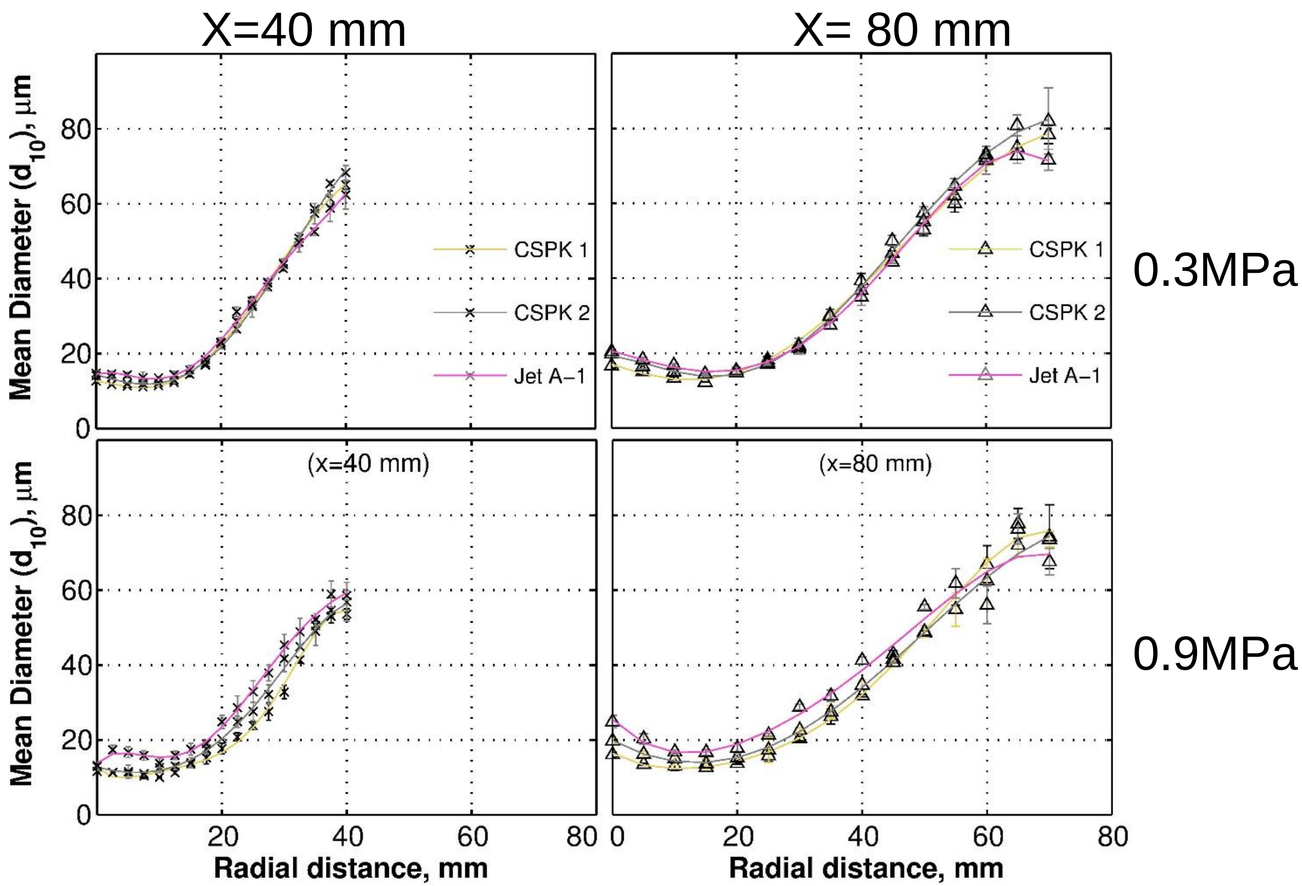
- Kumaran Kannaiyan and Reza Sadr, (2014) “Experimental study of the effect of fuel properties on Spray performance of alternative jet fuel”, ***Proceedings of ASME Turbo Expo 2014***, Vol. 3A, June 16-20, 2014, Dusseldorf, Germany, GT2014-25842.

- Kumaran Kannaiyan and Reza Sadr, (2013) “Spray Characteristics of Fischer-Tropsch Alternate Jet Fuels”, ***Proceedings of ASME Turbo Expo 2013: Power for Land, Sea and Air***, Vol.2, June 3-7, 2013, San Antanio, Texas, USA, GT2013-95761.

- Kumaran Kannaiyan and Reza Sadr, (2012) “Spray Characterization of Gas-to-Liquid Synthetic Aviation Fuels”, ***12th Triennial International conference on Liquid Atomization and Spray Systems (12th ICLASS)***, Heidelberg, Germany, September 2-6. (ISBN 978-88-903712-1-9)

Mean Droplet Diameter (d_{10})

Compared across fuels at,



Sauter Mean Diameter (d_{32})

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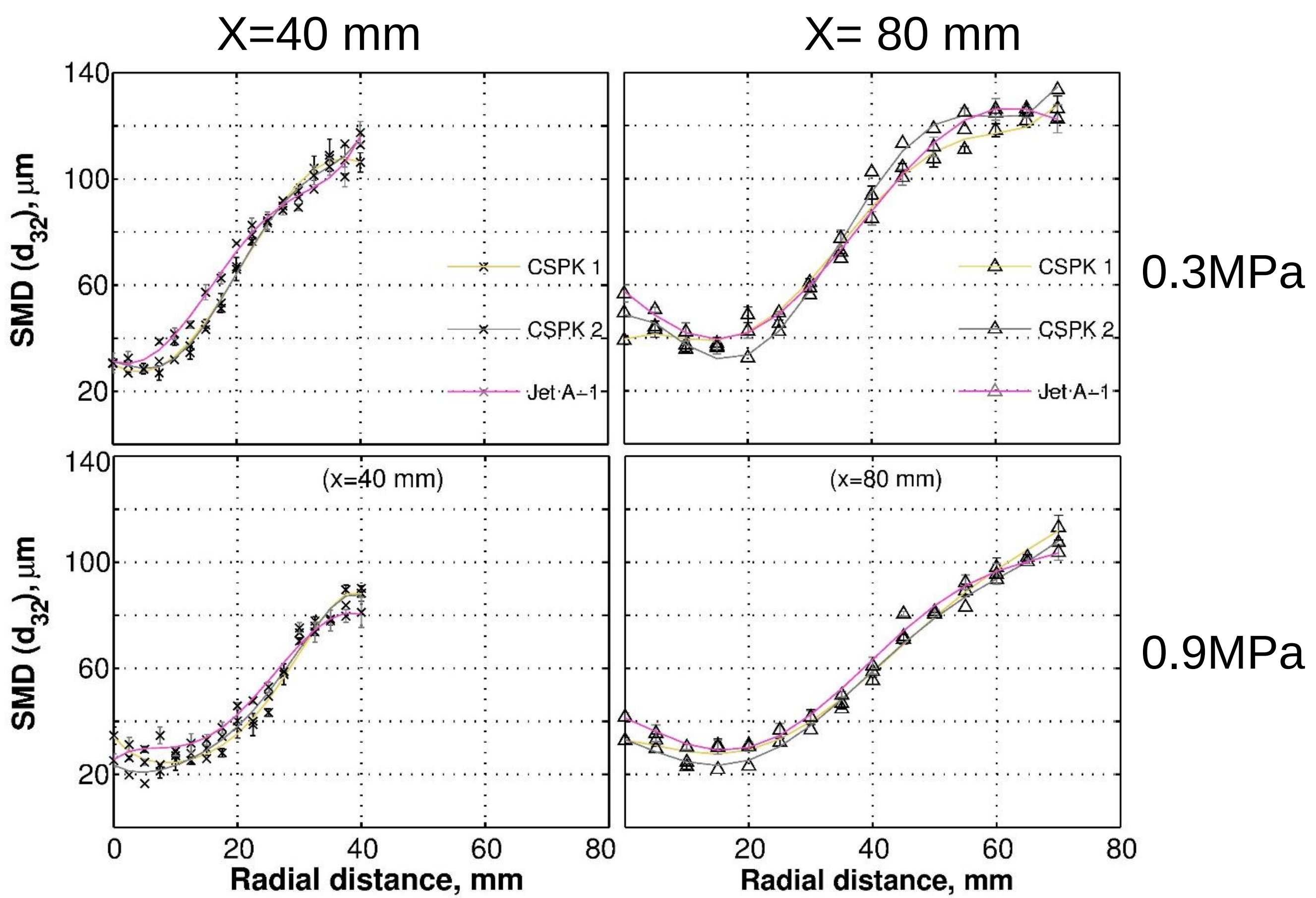
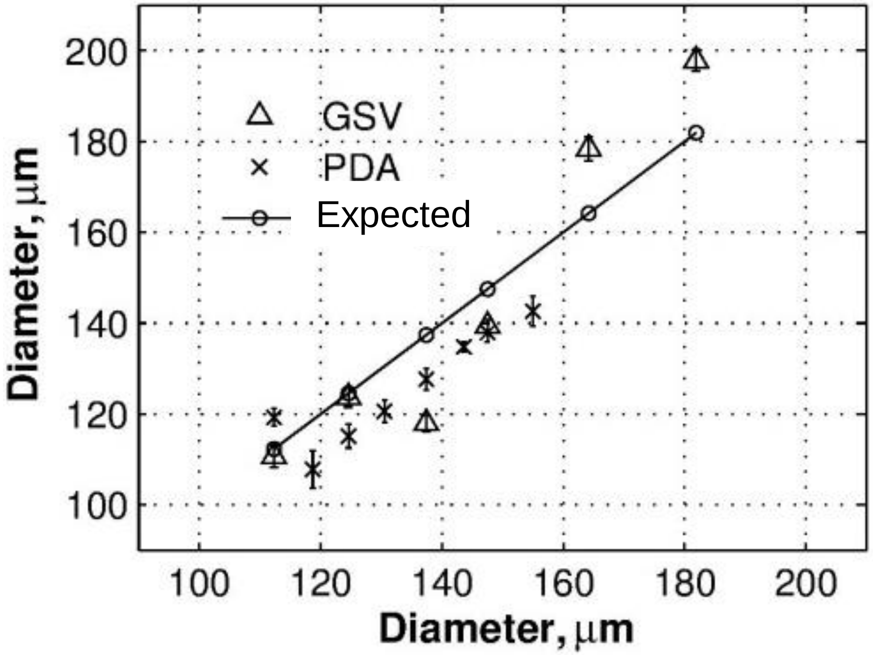
Compared across fuels at,

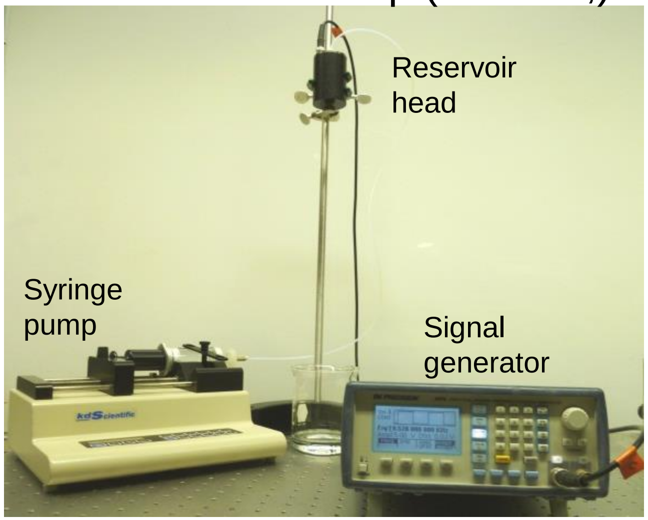


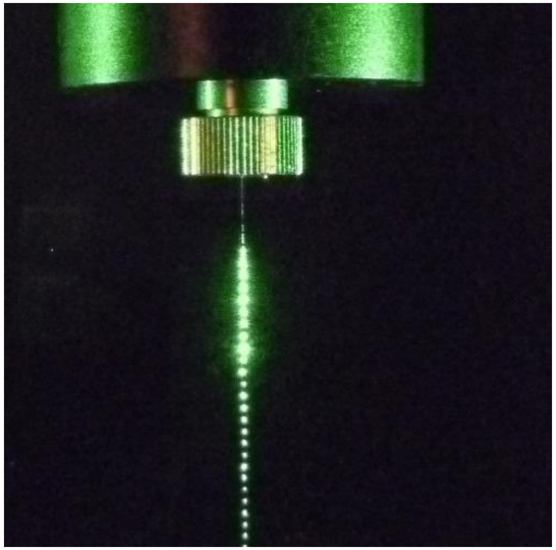
Verification

- Mono-disperse droplet generator (MDG) produces droplet diameters of known size
- Water is used to generate droplet diameters of known size
- GSV, PDA and expected diameters are within 10% agreement



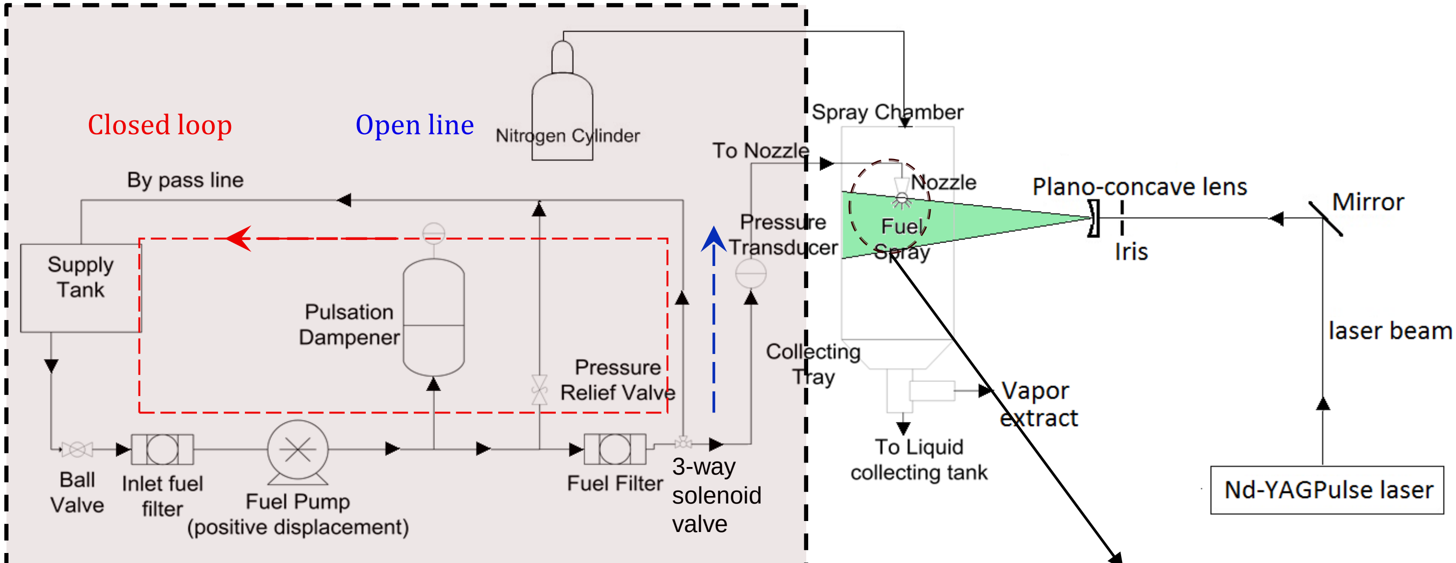
MDG-100 Setup (TSI Inc.,)



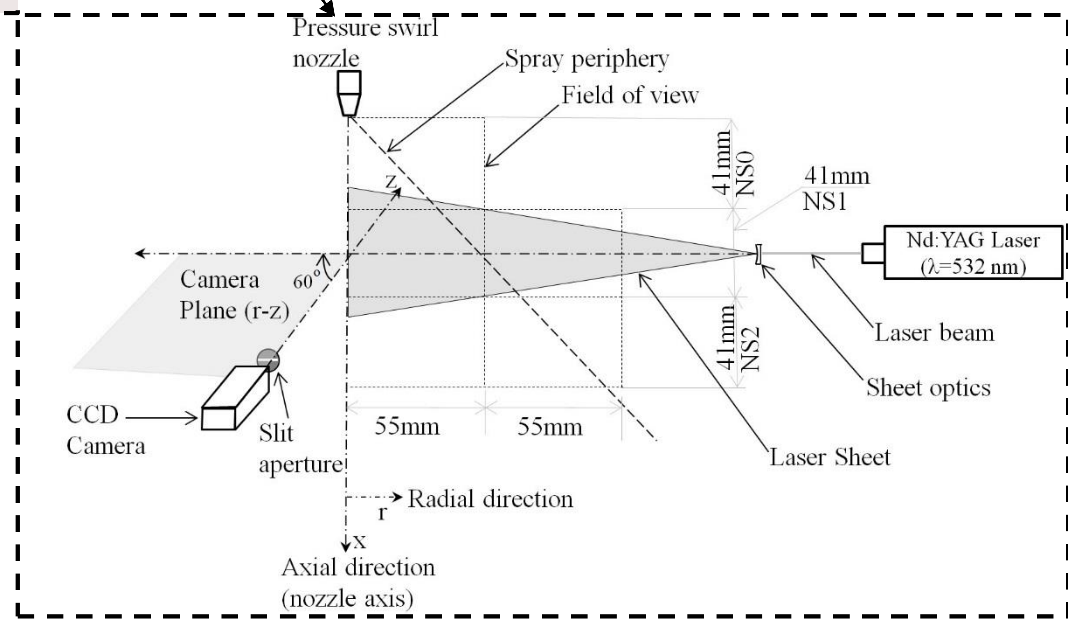


Water droplet stream from MDG

GSV Measurement Region



Fuel preparatory steps are the same for GSV & PDA measurements



SMD Comparison

- Estimated SMD using Lefebrve's (1987) empirical relation for Simplex nozzle,

$$SMD = 2.25.\sigma^{0.25}.\mu_l^{0.25}.\dot{m}_l^{0.25}.\Delta P_l^{-0.5}.\rho_a^{-0.25}$$

Injection pressure	SMD, µm (Estimate)		
	CSPK 1	CSPK 2	Jet A-1
0.3MPa	129	129	135
0.9MPa	93	95	98

GSV

- The SMD determined using GSV data is found to be higher than the estimated value by a maximum of 26% and 48% for 0.3MPa and 0.9MPa, respectively

Injection pressure	SMD, µm (GSV)		
	CSPK 1	CSPK 2	Jet A-1
0.3MPa	155	164	151
0.9MPa	136	138	145

PDA

- Droplet diameters that are collected within a common time window across all radial locations at a given axial location are used for global SMD calculation.
- Global SMD is found to be lower than the estimated SMD by a maximum of 28% and 16% for 0.3MPa and 0.9MPa, respectively

Injection pressure	SMD, µm (PDA)		
	CSPK 1	CSPK 2	Jet A-1
0.3MPa	96	98	95
0.9MPa	81	83	82

[Kumaran & Sadr, ASME Turbo Expo 2013, GT2013-95761]

Mean Droplet Diameter (d_{10})

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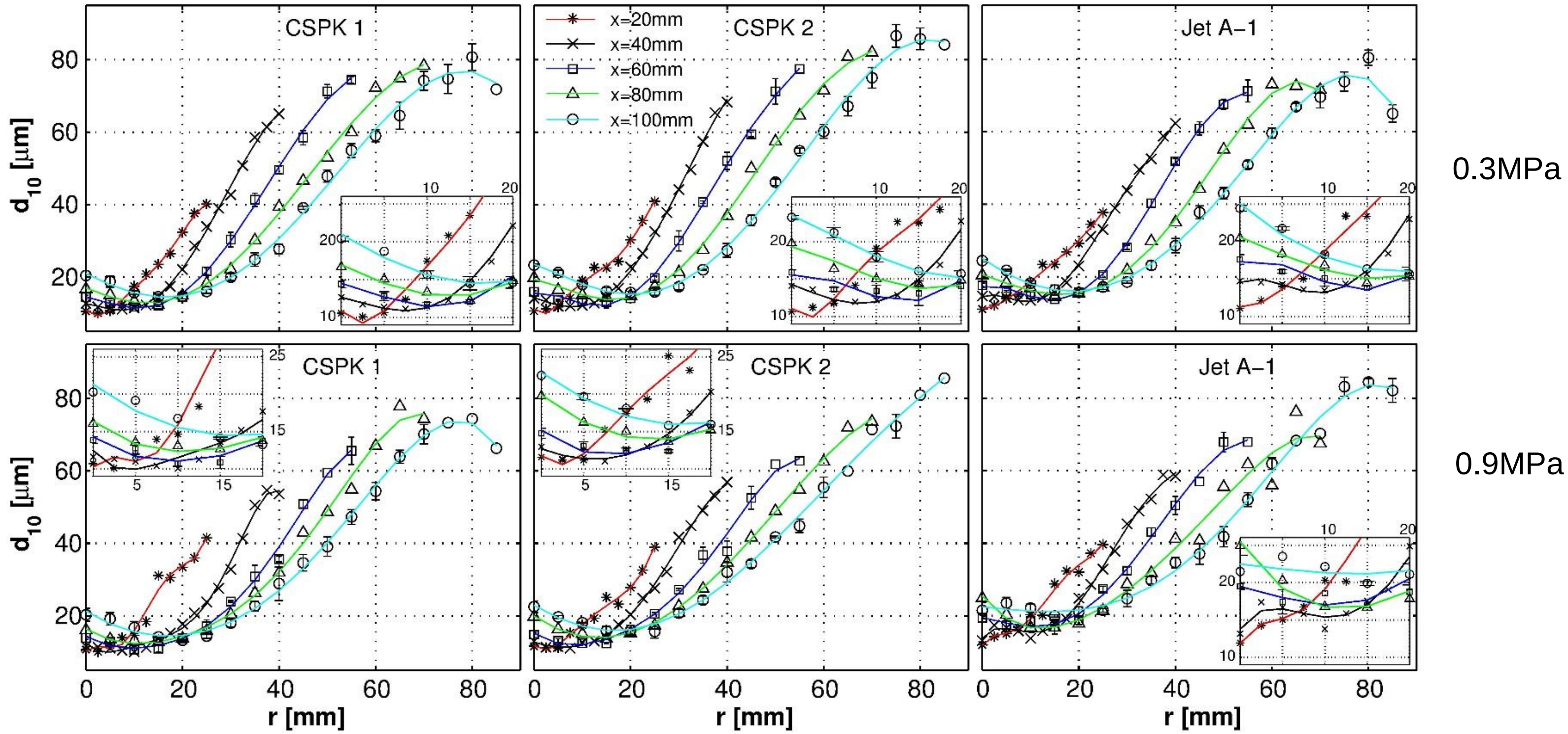

- Overall shape and trends are similar between the fuels.
- Typical standard deviation is shown as error bars only at two axial locations to facilitate the comparison

[Kumaran & Sadr, ASME Turbo Expo 2014, GT2014-25842]

Mean Droplet Velocity

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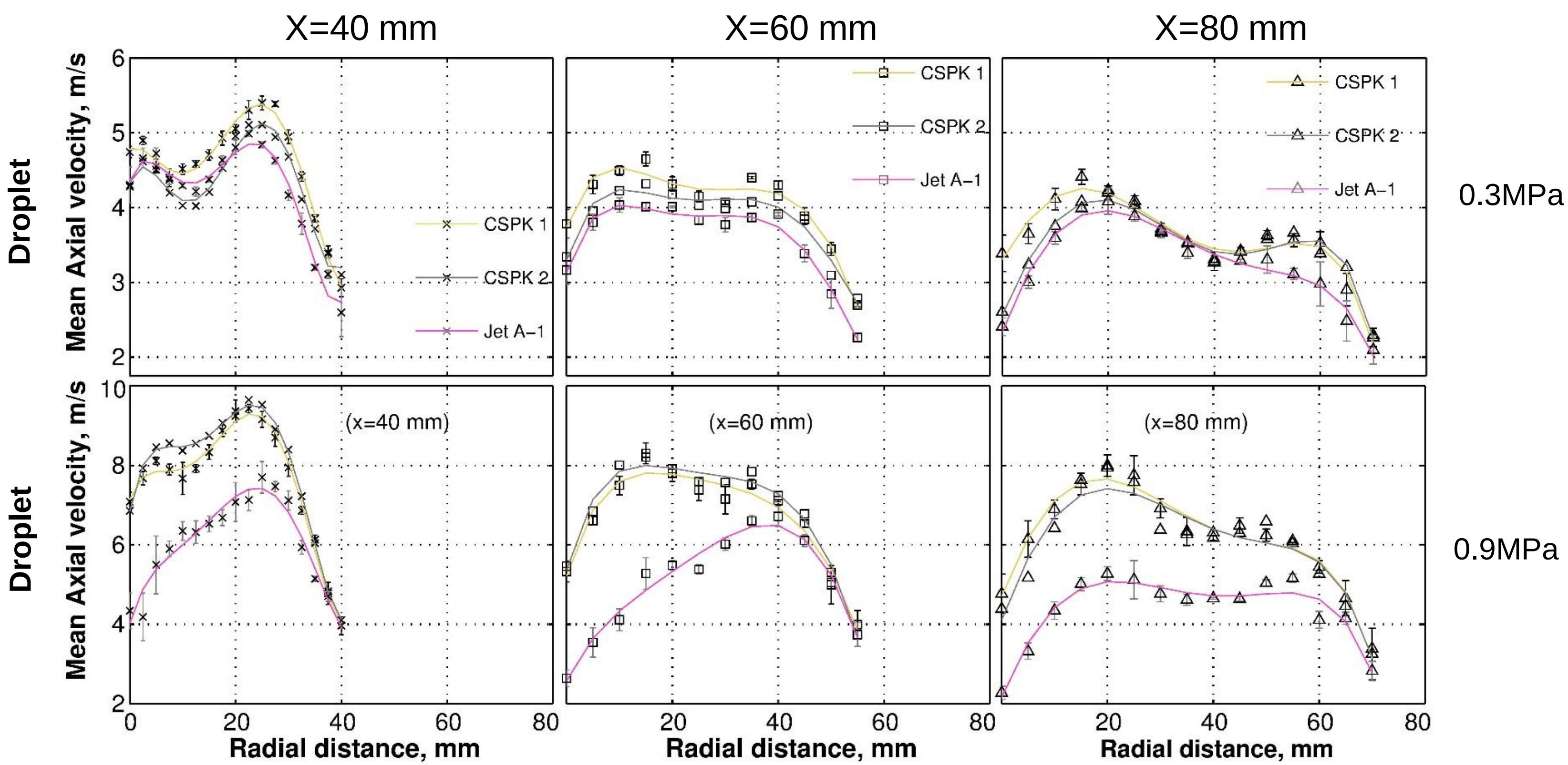

- Fuel with lower viscosity and density (CSPK 1) exhibits higher droplet mean axial velocity

- Trends are inline with those observed for the data rate

[Kumaran & Sadr, *Ener.Conv.Mang.*, 88, 1060-1069, 2014]