Studies of Evaporating Sprays; Issues & Diagnostic Tools

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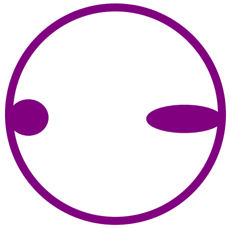
IEA Task Leaders Meeting, August 2006

Why Evaporating Sprays?

- Our motivation was initially driven by the need to understand the behaviour of the latest technology Gasoline Direct Injection fuel injection into realist temperatures and pressures (typically up-to ~15 bar and ~650K).
- The latest trend, similar to diesel engines, is to have spray-guided mixing where the injected fluid initially comprises of high momentum small droplets (~ 10 μm dia).
- Such sprays are typically very dense and limit the application of conventional methods such as PDA; further PDA is poor at measuring the liquid volume fraction.
- We explore the application of combined Mie-LIF to these sprays to measure average SMD diameters using the LSD approach.

Laser Sheet Dropsizing

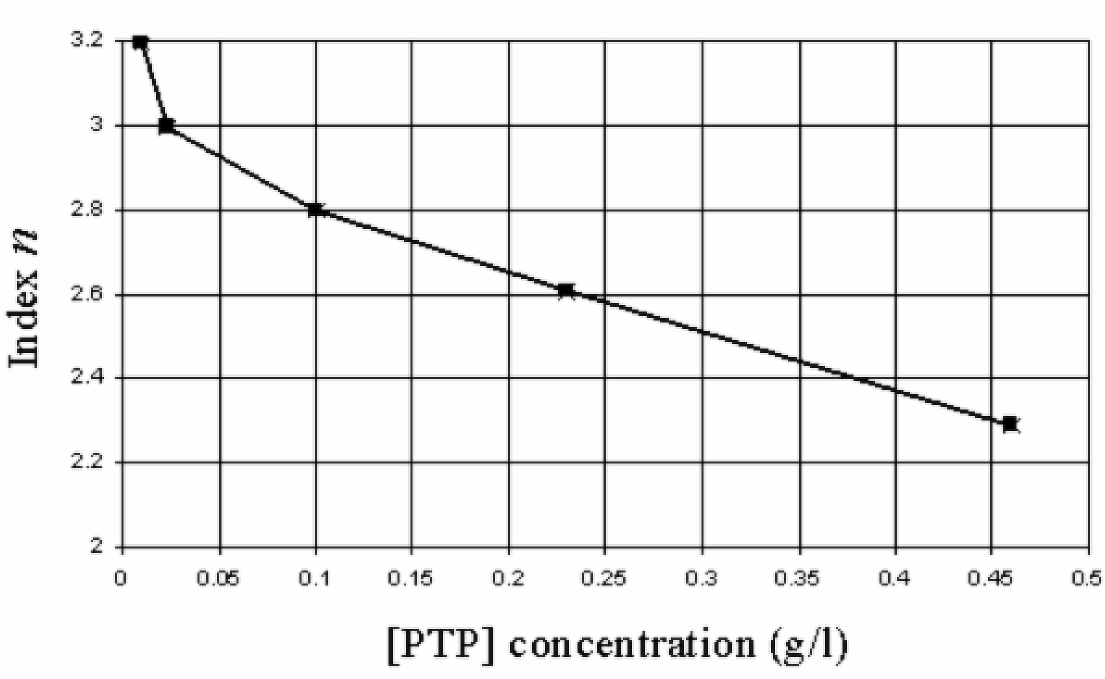


Mie Scattering $\rightarrow$ **d².**

LIF from optimum fluorophor conc

$\rightarrow$ **d³.**

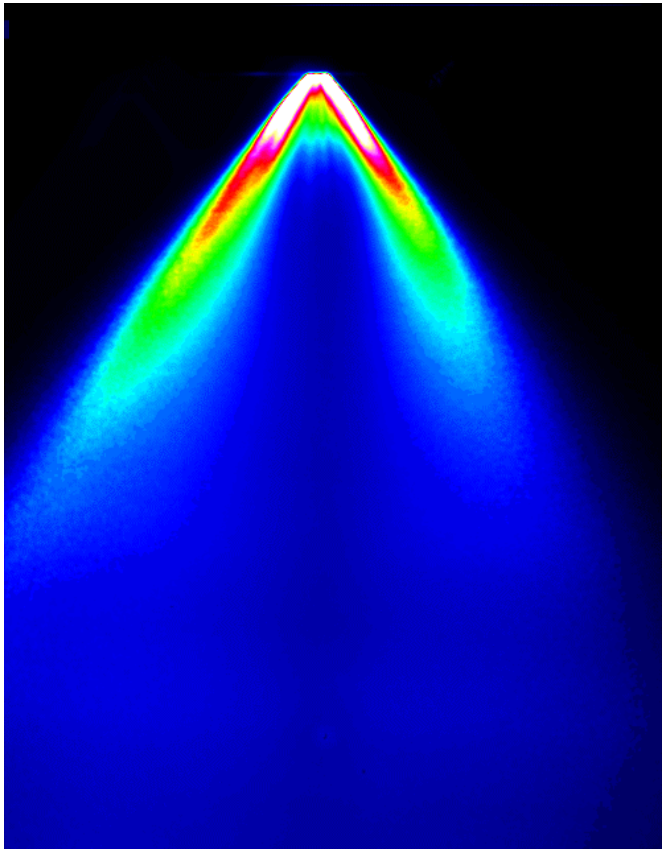
$$S_{LSD} = \frac{S_{LIF}}{S_{Mie}} = \frac{C_{LIF}\sum_i d_i^3}{C_{Mie}\sum_i d_i^2} \propto \frac{\sum_i d_i^3}{\sum_i d_i^2} \equiv d_{32}, \text{Sauter Mean Diameter.}$$



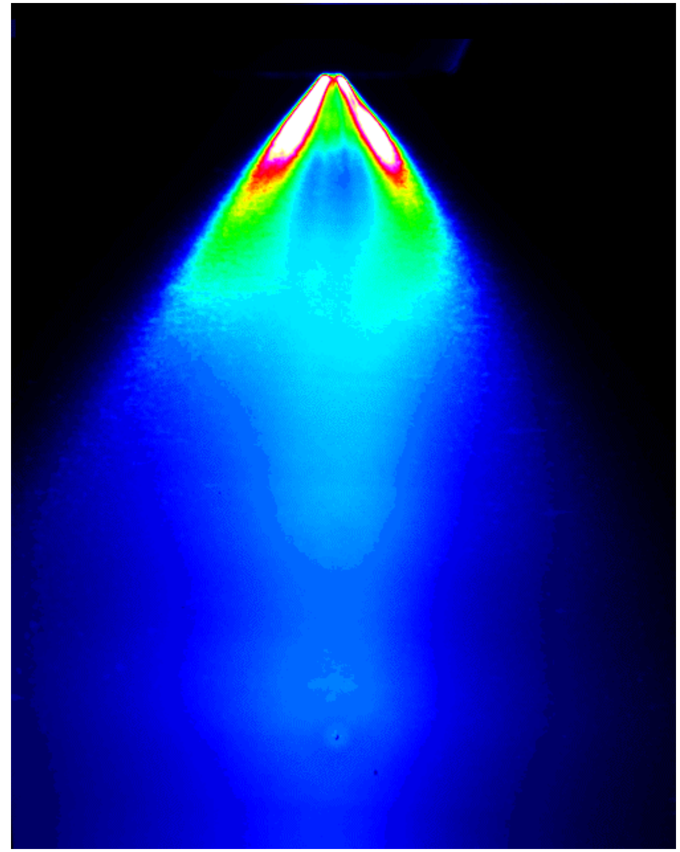
$$S_{LIF} \propto d_p^n$$

- Droplet LIF varies with the fluorescent agent concentration.
- High concentrations result in laser absorption mainly in the front surface of the droplet and therefore ⇒ "d_p^2" dependence.
- Low concentrations (optically thin) should give a "d_p^3" dependence, **but** "high gain" dyes give superadiant emission(ASE) and this generates more emission from larger droplets resulting in a "$d_p^{3+\delta}$" dependence [N.B. very small droplets can vary from this behaviour].

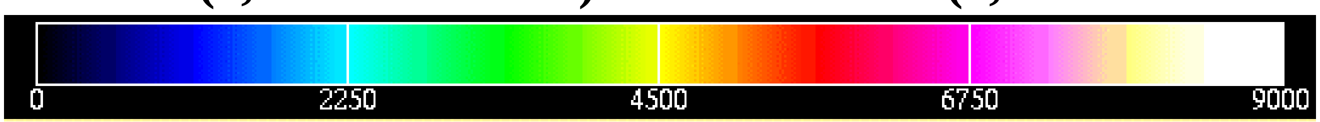
Mean LIF & Mie images from a Delavan pressure swirl atomiser.



Mean LIF (3,000 laser shots)

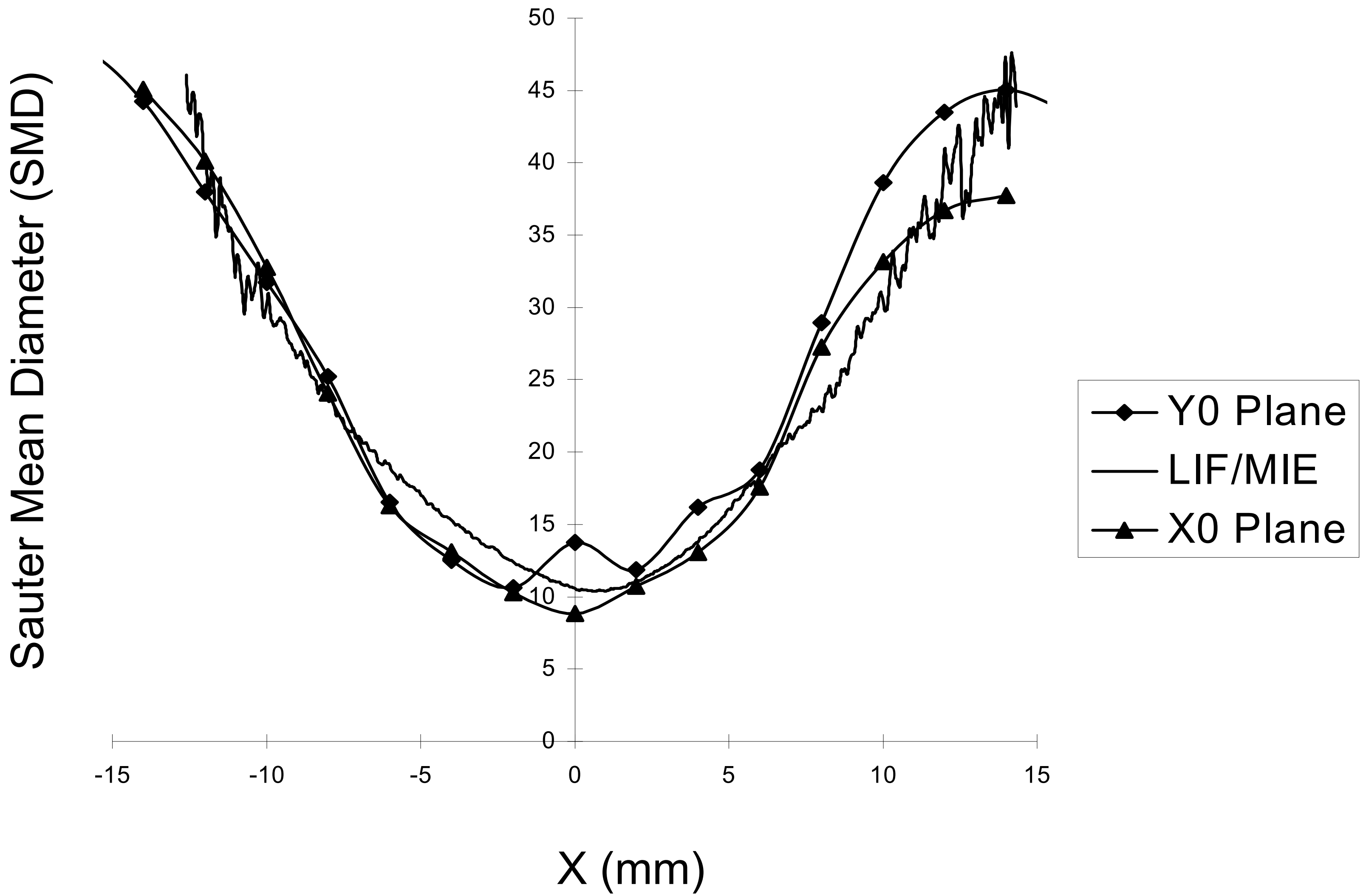


Mean Mie (3,000 laser shots)

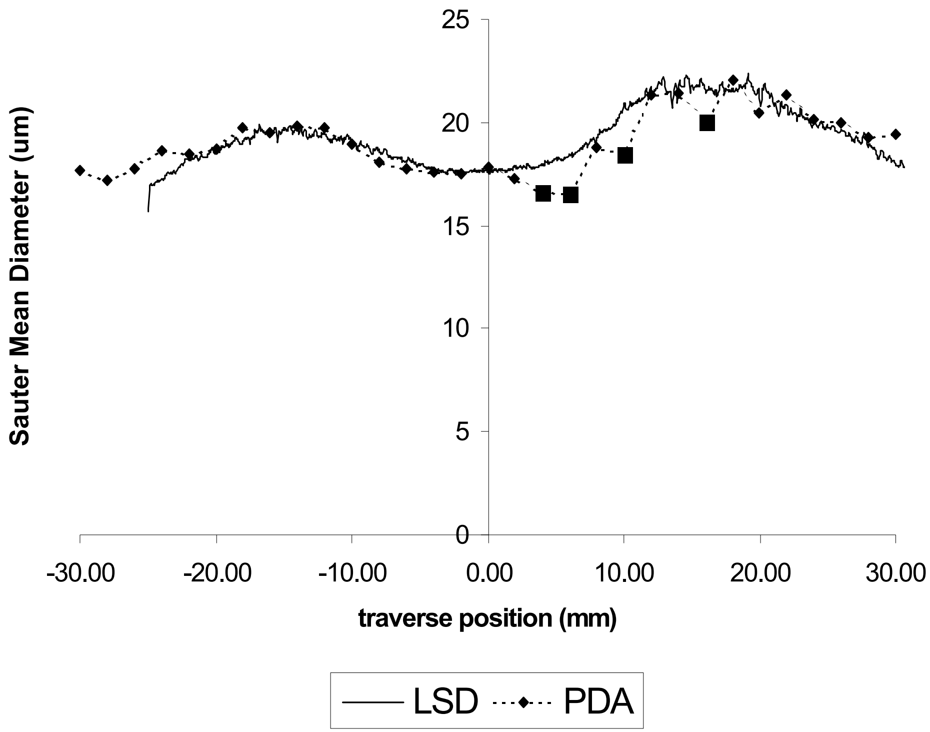


(False colours scale in counts)

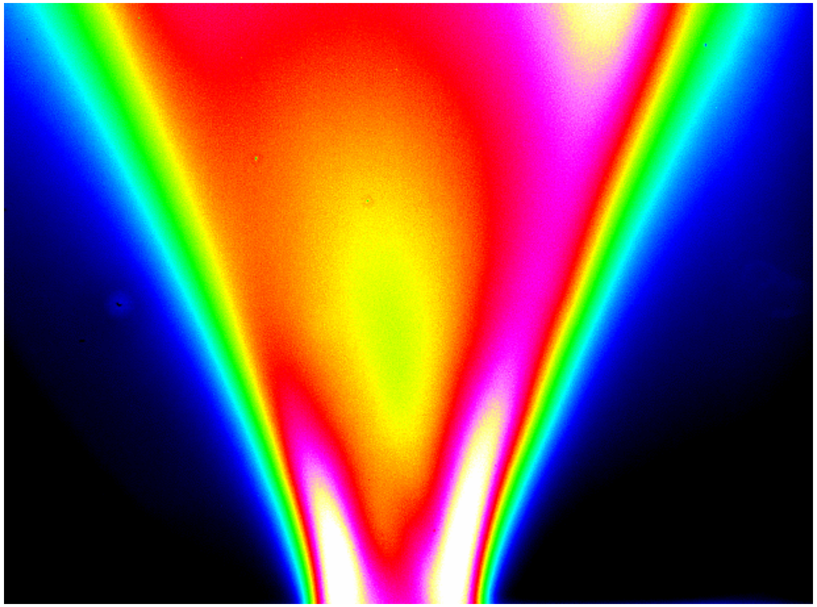
SMD comparison mean LSD versus PDA for a Delavan pressure swirl atomiser at z = 20mm downstream of the injector.



LSD on an "dense" Air-Spray Fuel Injector – an example of PDA issues.



Comparison of LSD & PDA.



Mean LIF Image - also a Map of Fuel Volume Fraction.

Extending LSD to evaporating sprays.

- PLIF is now widely used for in-cylinder mapping of fuel to estimate AFR or equivalence ratio.
- Tracers with good fluorescence properties and similar physical & chemical properties are used to mark the fuel.
- The temperature and pressure dependence of the tracers in the **vapour phase** are well established
- **How can we accommodate the P & T variations in a calibration?**
- **What is the fidelity of the tracers (e.g. do they co-evaporate & how sensitive to co-evaporation are we)?**

Tracer requirements

- The tracer SHOULD co-evaporate but we should also ask how important this is.
- Tracer LIF should be independent of T & P – through a careful selection of ketones this can achieve this to ~95%.
- Tracer should match the properties of the fuel – for this exercise we have restricted ourselves to the tractable problem of iso-octane.
- Tracer must give good d^3 response.

What do we know about droplet evaporation & mass transport ?

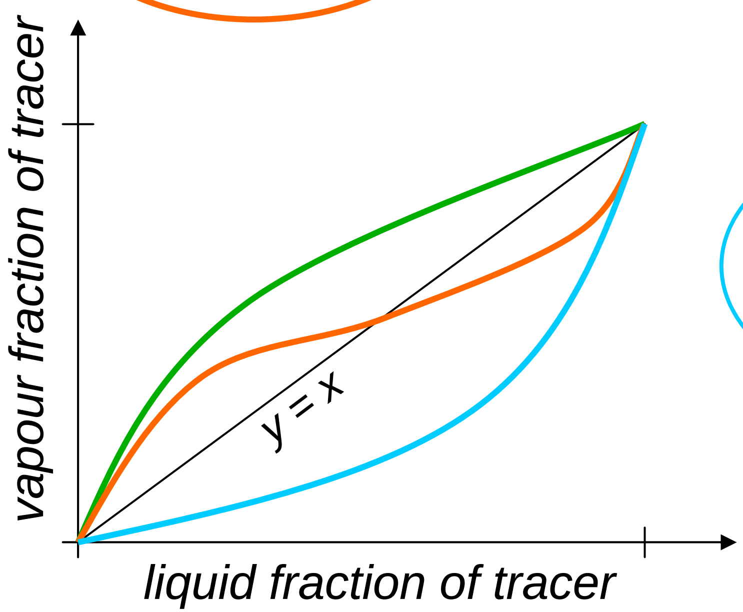
- In most systems the droplets do not survive for more than 2 msec and often less!
- In the previous data we see the relative droplet surface area decrease by nearly 100 in about 10° of c.a. at 1,000 rpm. This gives a reduction of 10 in droplet size or **1,000 in fuel mass fraction!**
- Typical mass evapouration rates are of ~10^{-6} m^2/sec whereas typical vapour mass diffusion rates are ~10^{-9} m^2/sec. This large difference will limit the distillation behaviour of droplets. This suggest flash evaporation will be important **unless** the air pressure is high.

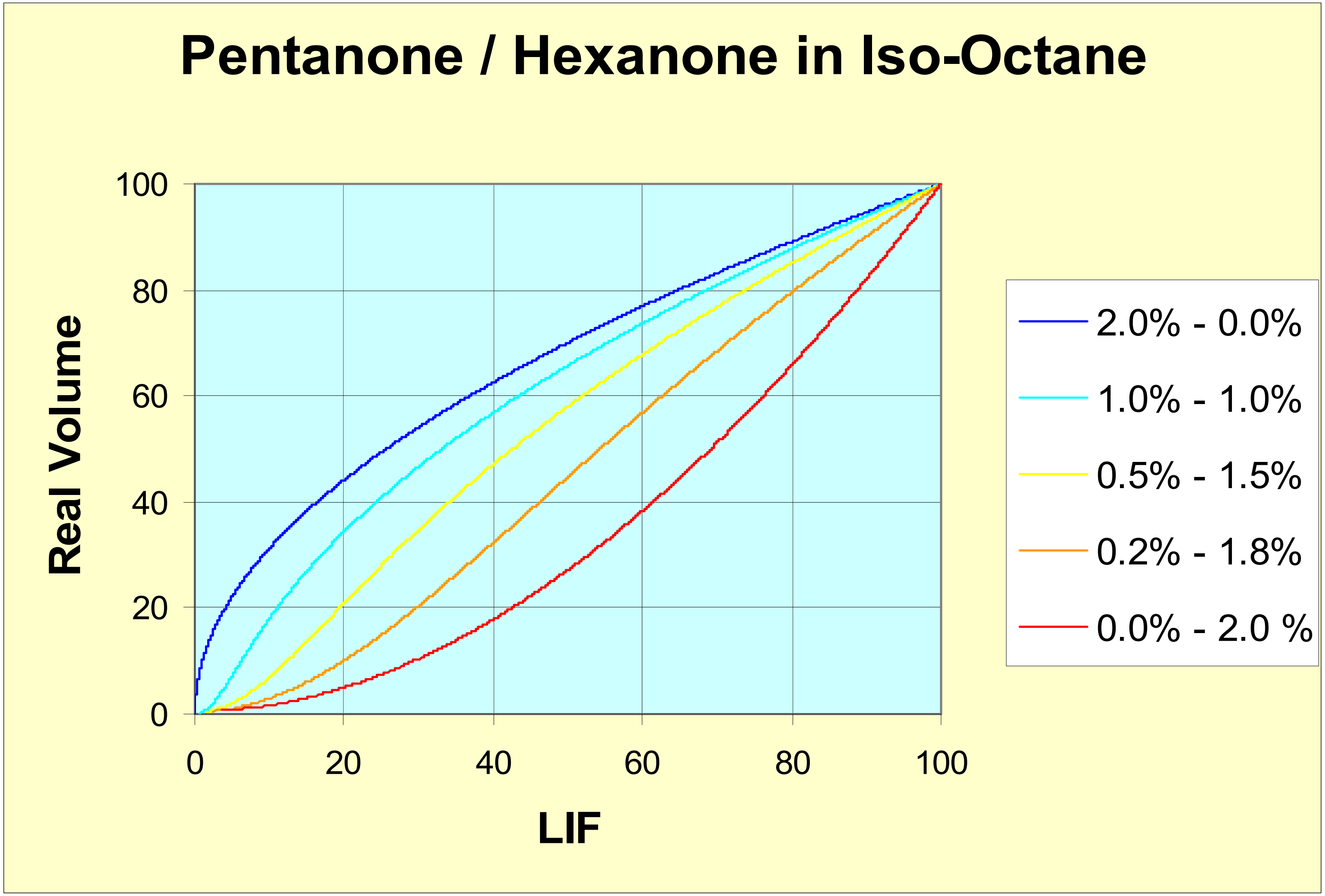
Two extreme evapouration regimes

Slow / Distillation Evapouration	Rapid / Flash Evapouration
diffusion rate >> evapouration rate	diffusion rate << evapouration rate
Differential evapouration	Homogeneous evapouration

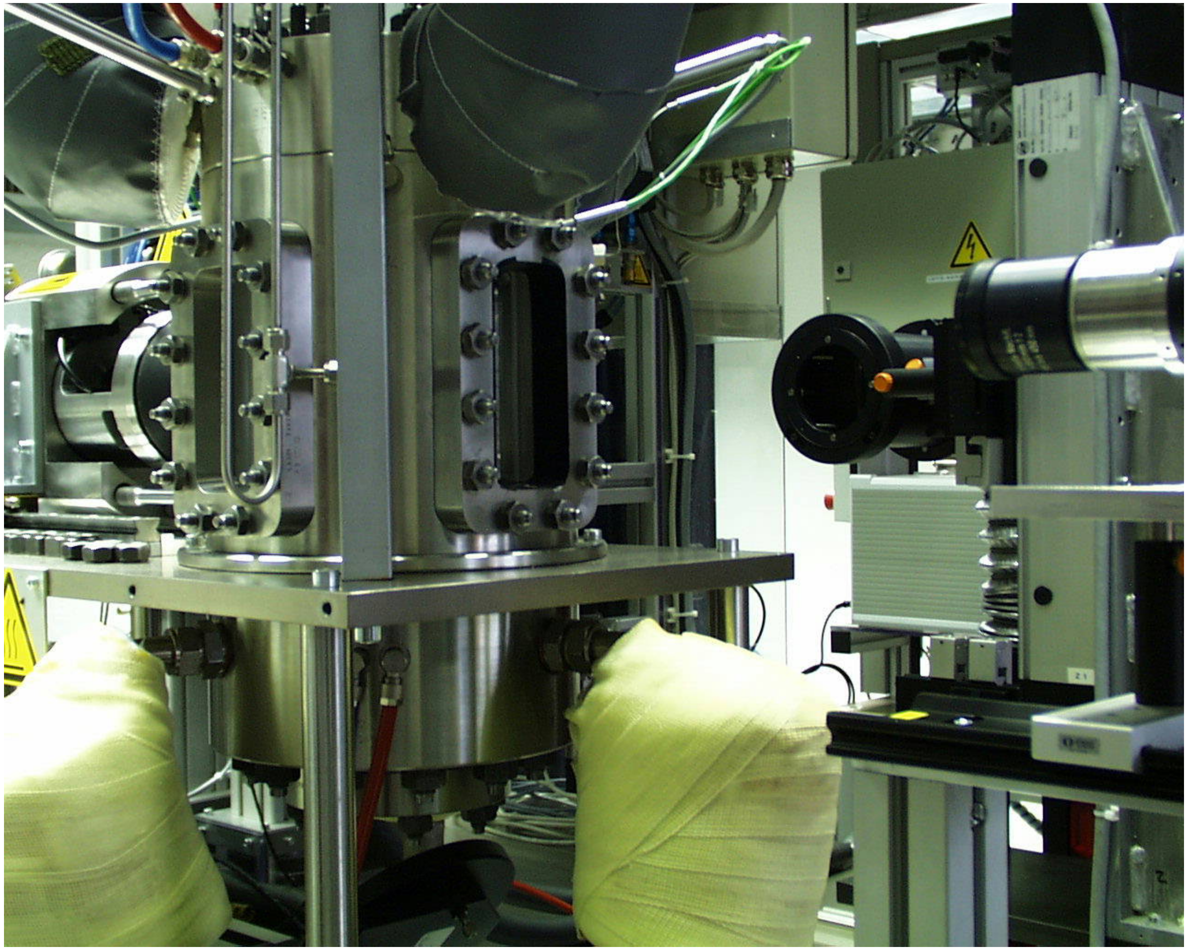
Slow / Distillation Evapouration for a « fuel + tracer » mixture

- Azetropic mixtures
- Non-Azetropic mixtures
  - Preferential evapouration of the fuel
  - Preferential evapouration of the tracer




Pentanone / Hexanone in Iso-Octane
Real Volume
100
80
60
40
20
0
0
20
40
60
80
100
LIF
2.0% - 0.0%
1.0% - 1.0%
0.5% - 1.5%
0.2% - 1.8%
0.0% - 2.0 %

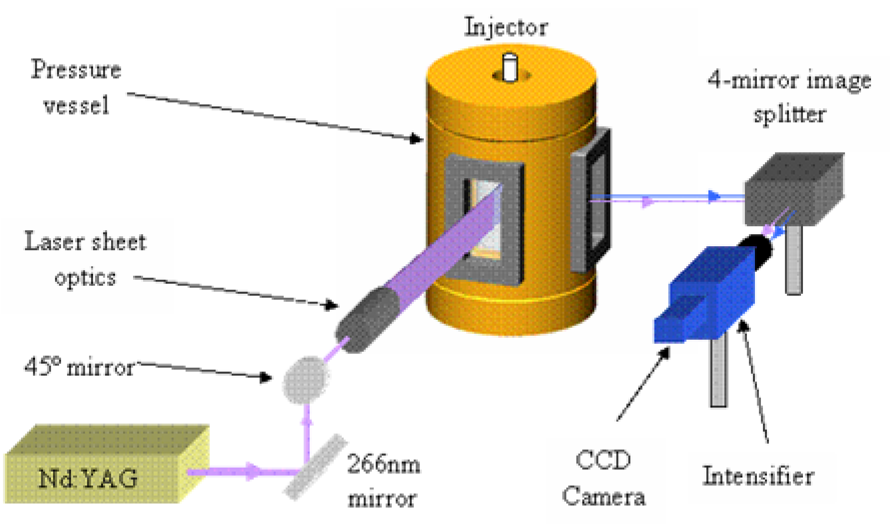
BMW Optical Bomb for Injector Testing

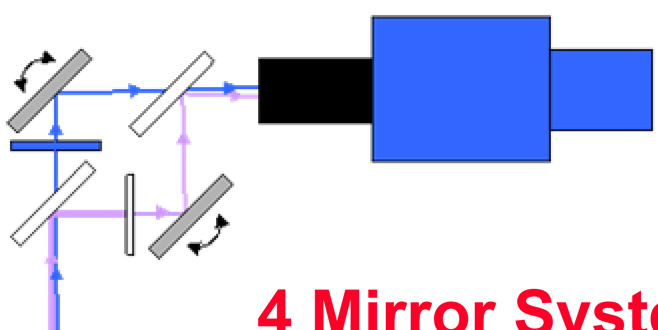


- Operates on pure N_2 flow, P to 20 bar & T to 700K.
- Continuous flow therefore allows multiple repeat injections.
- Fuel pressure to 200 bar.

Experimental Details – 2 Nearly Identical Pressure Vessels

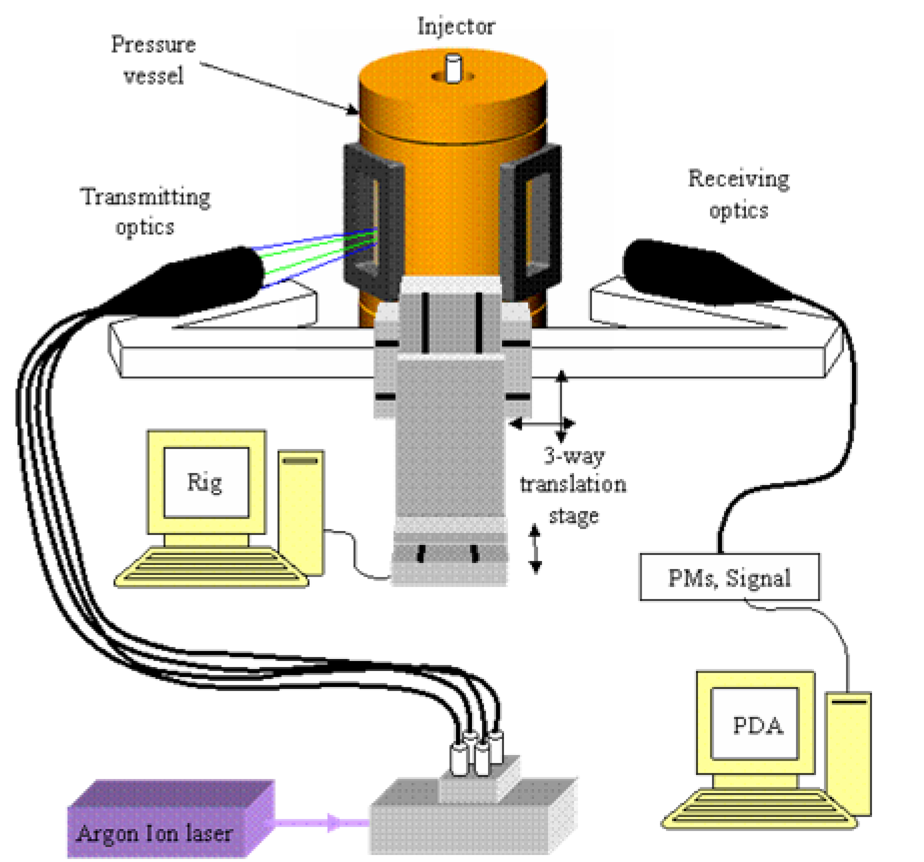
LSD – Mie - LIF





4 Mirror System

PDA



LSD Images

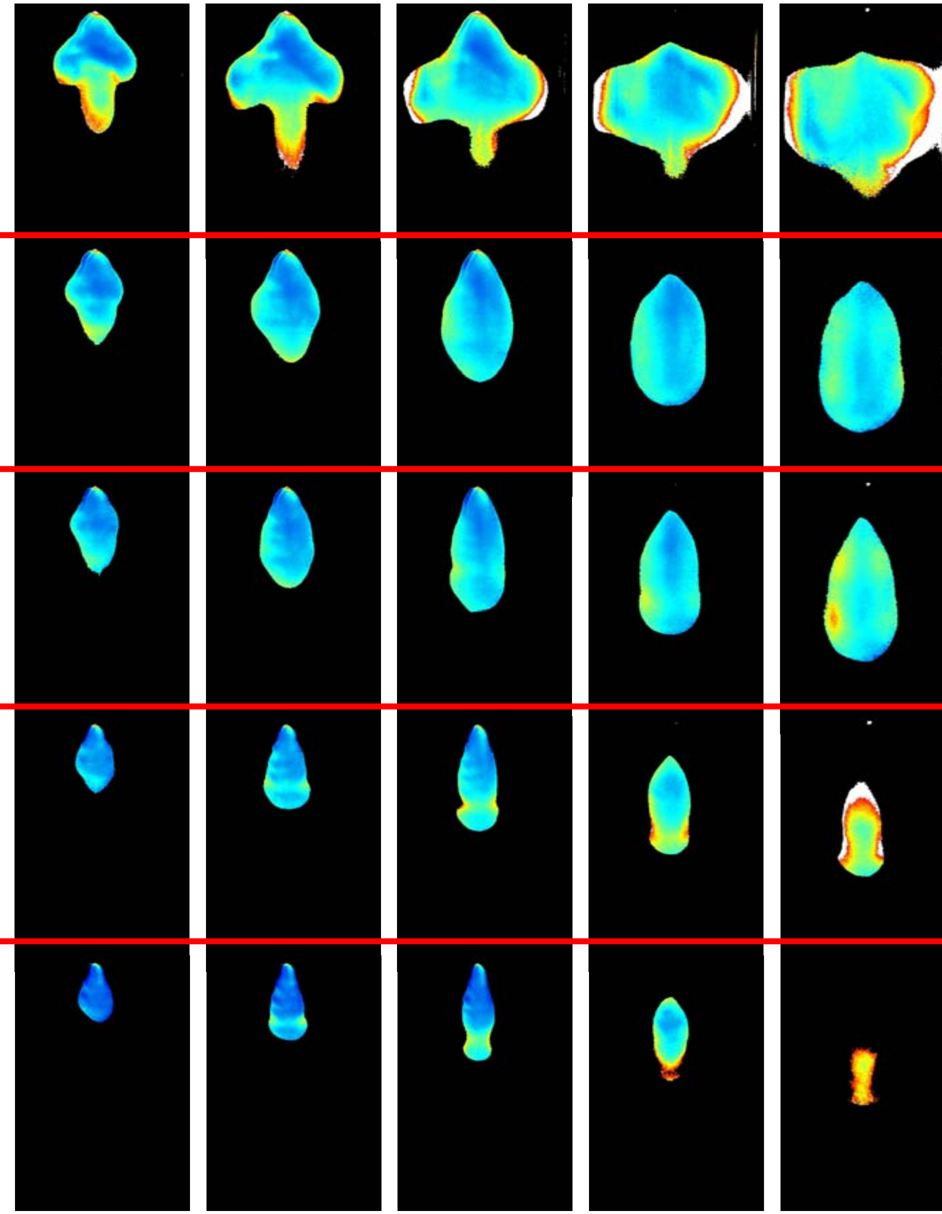
1bar - 25°C

3bar - 135°C

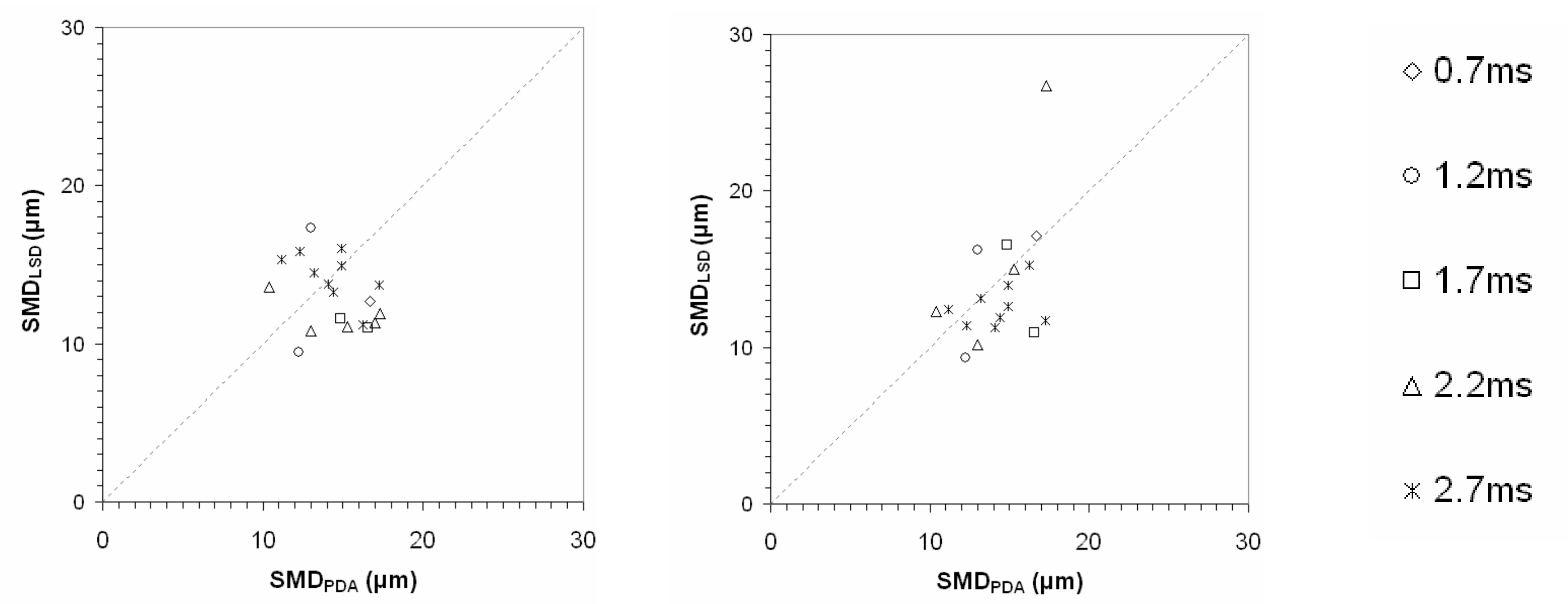
5bar - 197°C

10bar - 297°C

15bar - 365°C

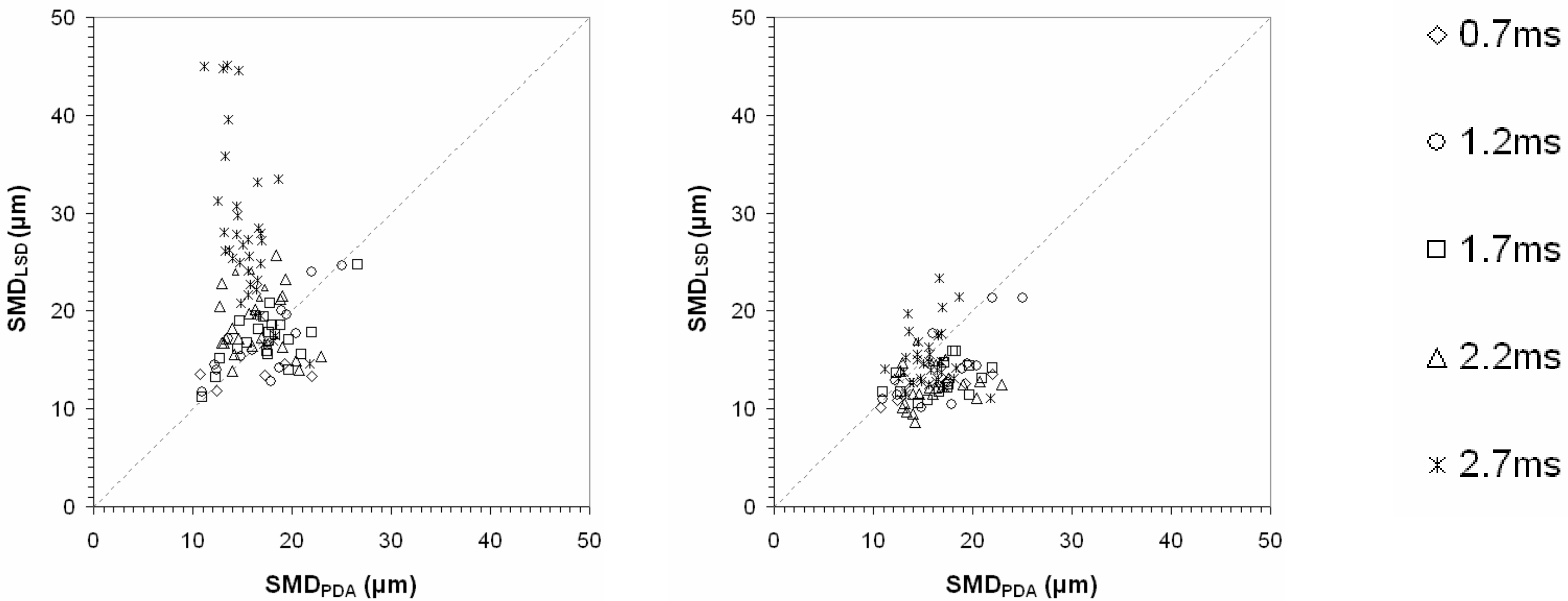


LSD & PDA Comparison @ 1bar - 25ºC



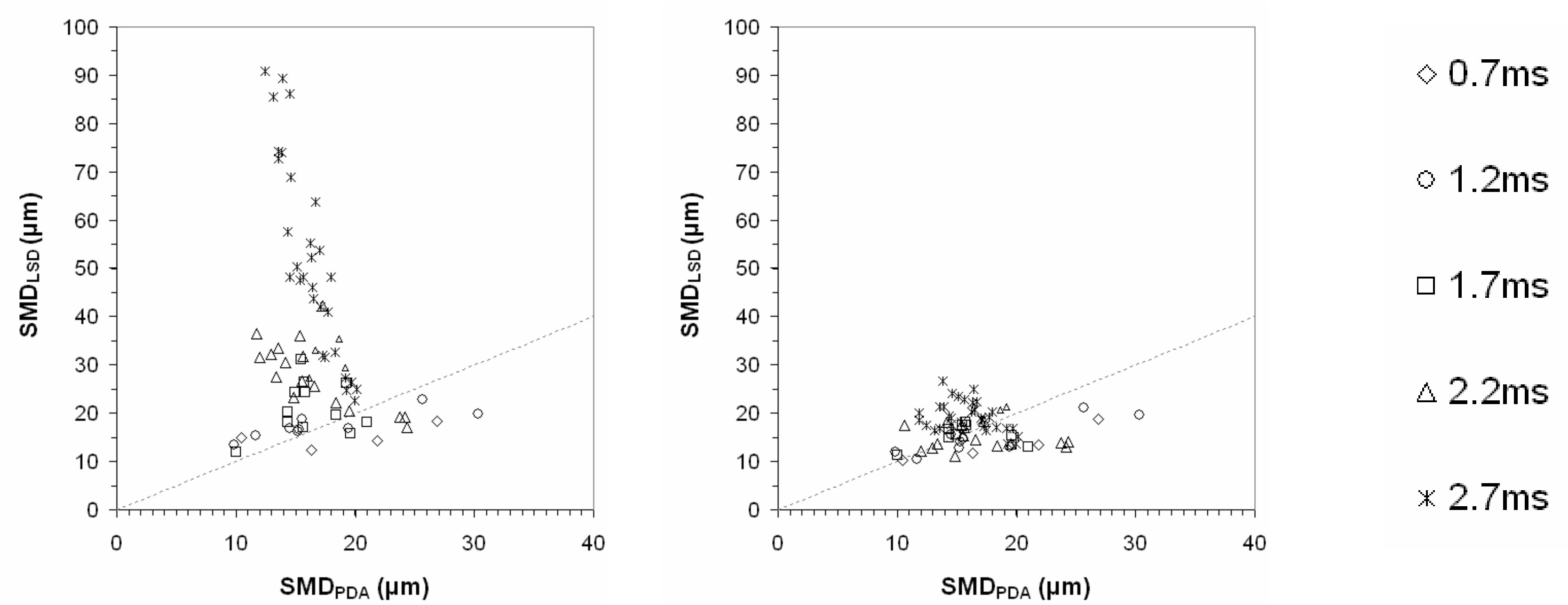
Various times after start of injection - 2 / 0 / 98 (%pentanone/%hexanone/%iso-octane) (left) & 0.5 / 1.5 / 98 mixtures (right)

LSD & PDA Comparison @ 3bar - 135ºC



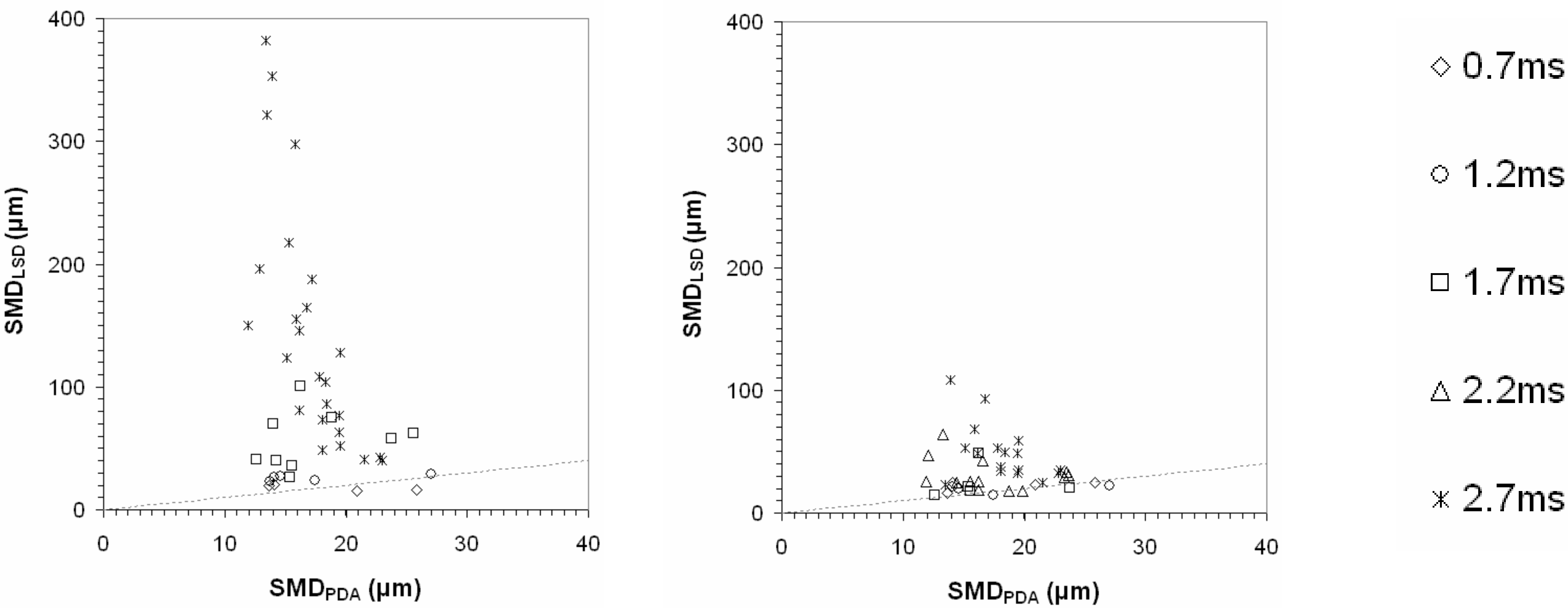
Various times after start of injection - 2 / 0 / 98 (%pentanone/%hexanone/%iso-octane) (left) & 0.5 / 1.5 / 98 mixtures (right)

LSD & PDA Comparison @ 5bar - 195ºC



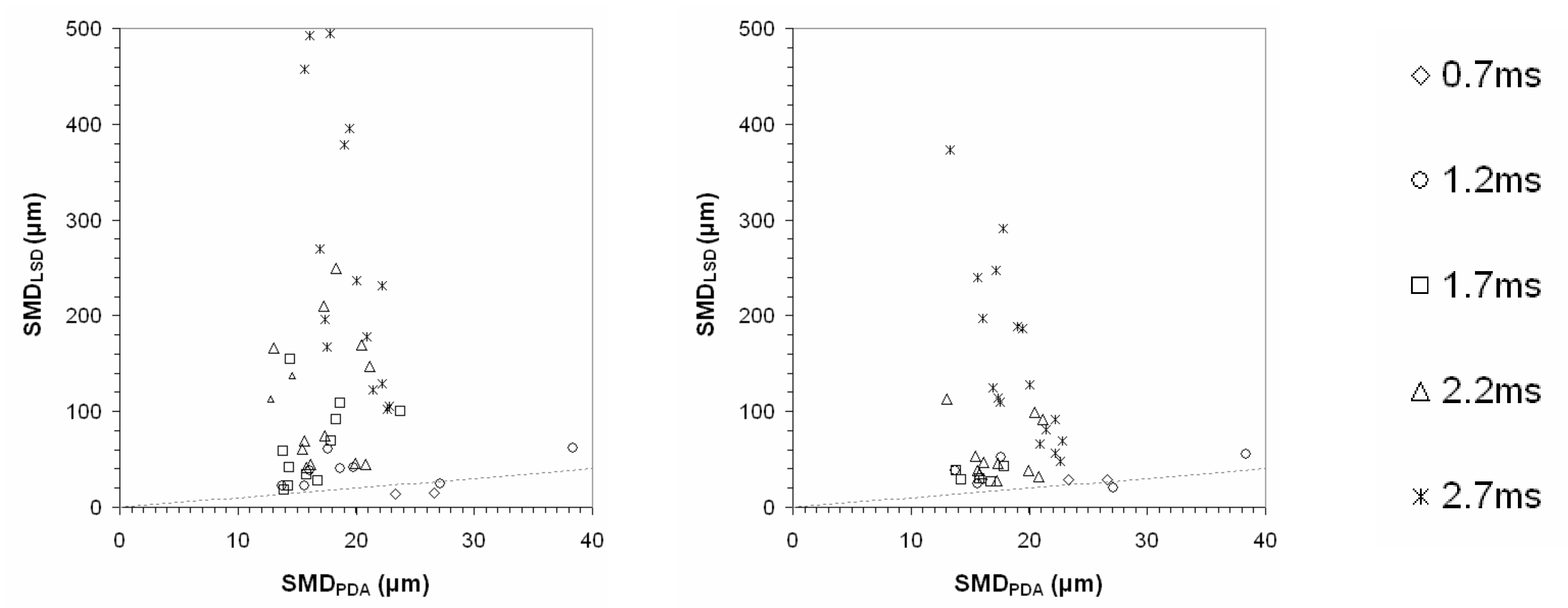
Various times after start of injection - 2 / 0 / 98 (%pentanone/%hexanone/%iso-octane) (left) & 0.5 / 1.5 / 98 mixtures (right)

LSD & PDA Comparison @ 10 bar - 295ºC



Various times after start of injection - 2 / 0 / 98 (%pentanone/%hexanone/%iso-octane) (left) & 0.5 / 1.5 / 98 mixtures (right)

LSD & PDA Comparison @ 15 bar - 360ºC



Various times after start of injection - 2 / 0 / 98 (%pentanone/%hexanone/%iso-octane) (left) & 0.5 / 1.5 / 98 mixtures (right)

Conclusions:

- PDA struggles with high density, small droplet size sprays and is not suitable as a routine diagnostic as the measurements times (hours) and data processing (days) is too long.
- We have found a combination of LIF tracers suitable for iso-octane sprays operating up to modest evaporation rates.
- Our comparison with real sprays show that the LSD technique is good to ~5 bar and 200°C.
- At high evaporation rates LIF of vapour confuses the issue.
- At high evaporation rates LIF directly measures the liquid volume fraction and is arguably the best diagnostic. At these conditions large increases in the LIF/Mie ration can be interpreted as indicators of rapid evaporation.
- The next challenges are to:
  - Look at diesel sprays.
  - To understand sprays undergoing super-critical evaporation.