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The Effect of Fuel Volatility and Aromatic Content on Particulate Emissions

May 18 2012

Outline

- Introduction
  - Honda paper
- Fuel design
  - Component selection
  - Raoult's law
  - UNIFAC
- Experimental procedure
  - Engine and operating point
  - Test points
- Instrumentation
- Results
  - Model fuels
  - EN228 Gasoline
  - EU5 Reference fuel
- Conclusions

What effect do aromatic content and fuel volatility have on particulate emissions?

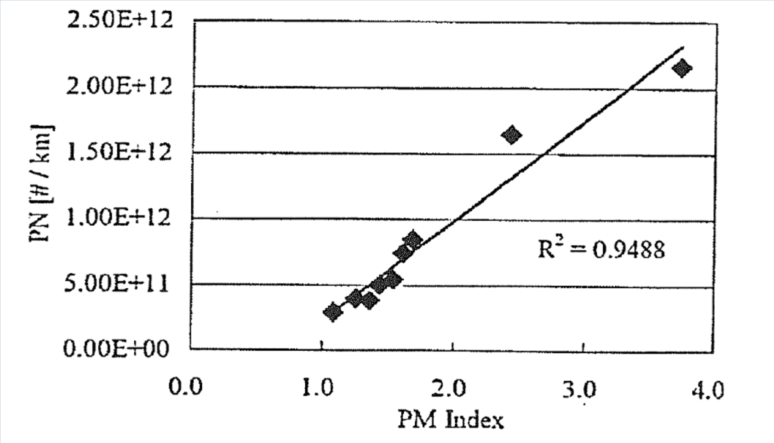
- SAE 2010-01-2115 paper "Development of a predictive model for gasoline vehicle particulate matter emissions" (Aikawa, Sakurai, & Jetter)
- Honda PM number index: $I(VP, DBE) = \sum_{i=1}^{n} \left[\frac{DBE_i + 1}{VP_i}\right] W_{ti}$
- DBE: Double bond equivalent
  - A measure of how unsaturated a Hydrocarbon is
  - $DBE = \frac{2C - H - N + 2}{2}$
- No independent control of volatility and DBE. PFI engine only.
- Aim:
  - Verify index and extend to SGDI combustion system

Honda paper

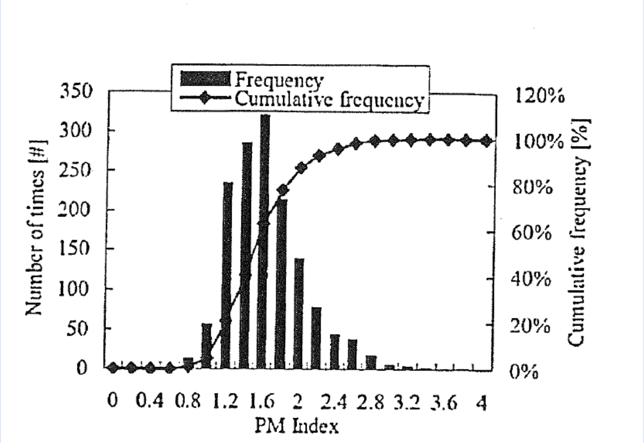
- **Base fuel + 10% additives**
  - **2,2,4-Trimethylpentane**
  - **Dodecane**
  - **Ethylbenzene**
  - **1,2,4-Trimethylbenzene**
  - **Ethanol**

- **PM index range 1.01 – 3.86**

- **Range of worldwide fuels tested**



Relationship between PN (#/km) and PM index over NEDC (Aikawa, 2010)



Range of PM indexes of a selection of commercially available fuels worldwide (Aikawa, 2010)

Fuel composition

	T_b (K), 1.01325 bar	RON	BON
n-pentane	309.2	62	60
iso-octane	372.4	100	100
n-octane	398.8	-17	-19
75/25 io/no mix	379*	n/a	70*
Toluene	383.8	104	120
iso-decane	433.5	100	126
n-decane	447.3	-17	-41
24/76 id/nd mix	444*	n/a	-1*
1,3,5-Trimethylbenzene	437.9	n/a	161

Aromatic component selection based on BP and RON

* Linear average

Fuel design

Raoult's law

- Raoult's law relates the vapour pressure of an ideal solution to the vapour pressure of each of its chemical components by the molar fraction of each component present

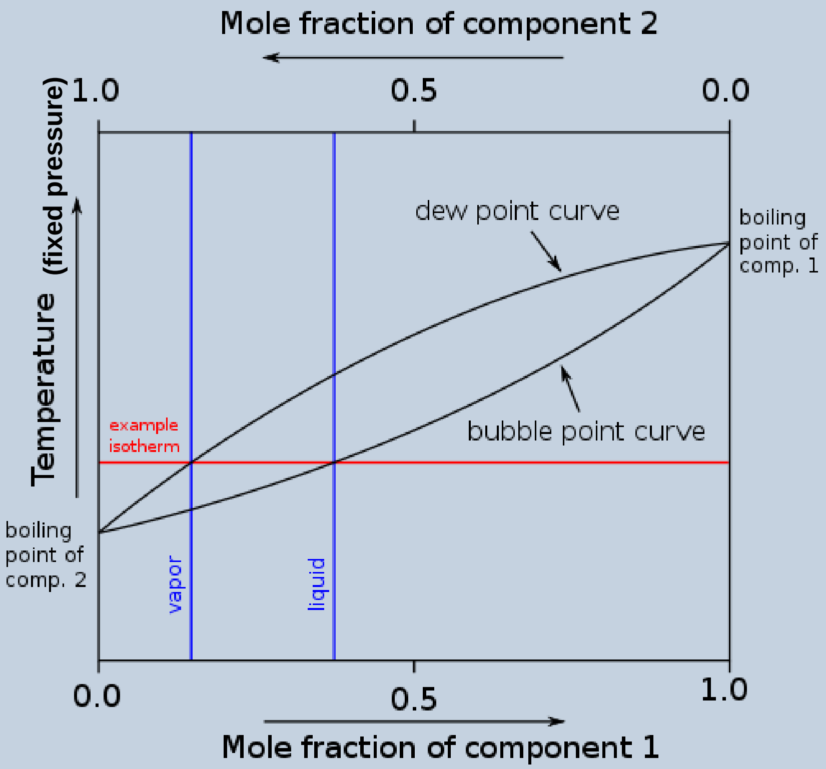
- $y_i P = x_i P_{vpi}$ [Poling, Prausnitz, & O'Connell]

  y_i: molar fraction of component *i* in vapour

  x_i the molar fraction of component *i* in liquid

  P_{vpi} the vapour pressure of component *i*

  P the partial pressure of the component.



- Assumptions:
  - Neglect effect of surface tension and any external conditions (electric/magnetic field etc)
  - Ideal mixing ➔ linear relationship

Fuel design

UNIFAC*

- UNIversal Functional Activity Coefficient (UNIFAC)
- Attempts to extend Raoult's Law to account for non-ideal mixing
- Semi-empirical model to predict non-ideal mixture behaviour based on molecular size and interactions
- Breaks molecules into functional groups to model interactions
- Cannot be used on electrolytes

$$\ln \gamma_i = \underset{\text{combinatorial}}{\ln \gamma_i^c} + \underset{\text{residual}}{\ln \gamma_i^R}$$

$$\ln \gamma_i^c = \ln \frac{\Phi_i}{x_i} + \frac{z}{2} q_i \ln \frac{\theta_i}{\Phi_i} + l_i - \frac{\Phi_i}{x_i} \sum_j x_j l_j$$

$$\ln \gamma_i^R = q_i \left[1 - \ln \left(\sum_j \theta_j \tau_{ji} \right) - \sum_j \frac{\theta_j \tau_{ij}}{\sum_k \theta_k \tau_{kj}} \right]$$

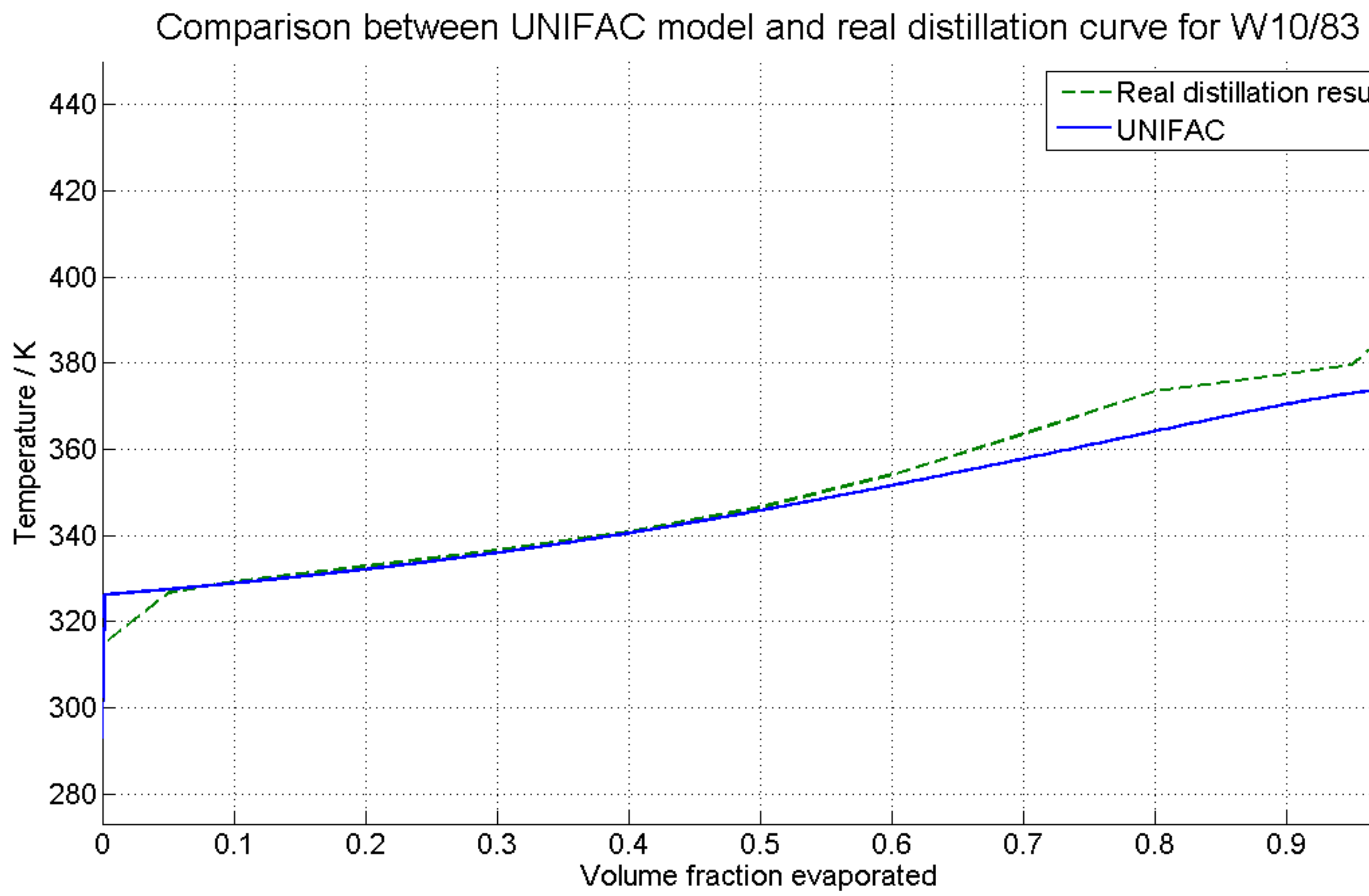
$$l_i = \frac{z}{2}(r_i - q_i) - (r_i - 1) \quad z = 10$$

$$\theta_i = \frac{q_i x_i}{\sum_j q_j x_j} \quad \Phi_i = \frac{r_i x_i}{\sum_j r_j x_j} \quad \tau_{ji} = \exp\left(-\frac{u_{ji} - u_{ii}}{RT} \right)$$

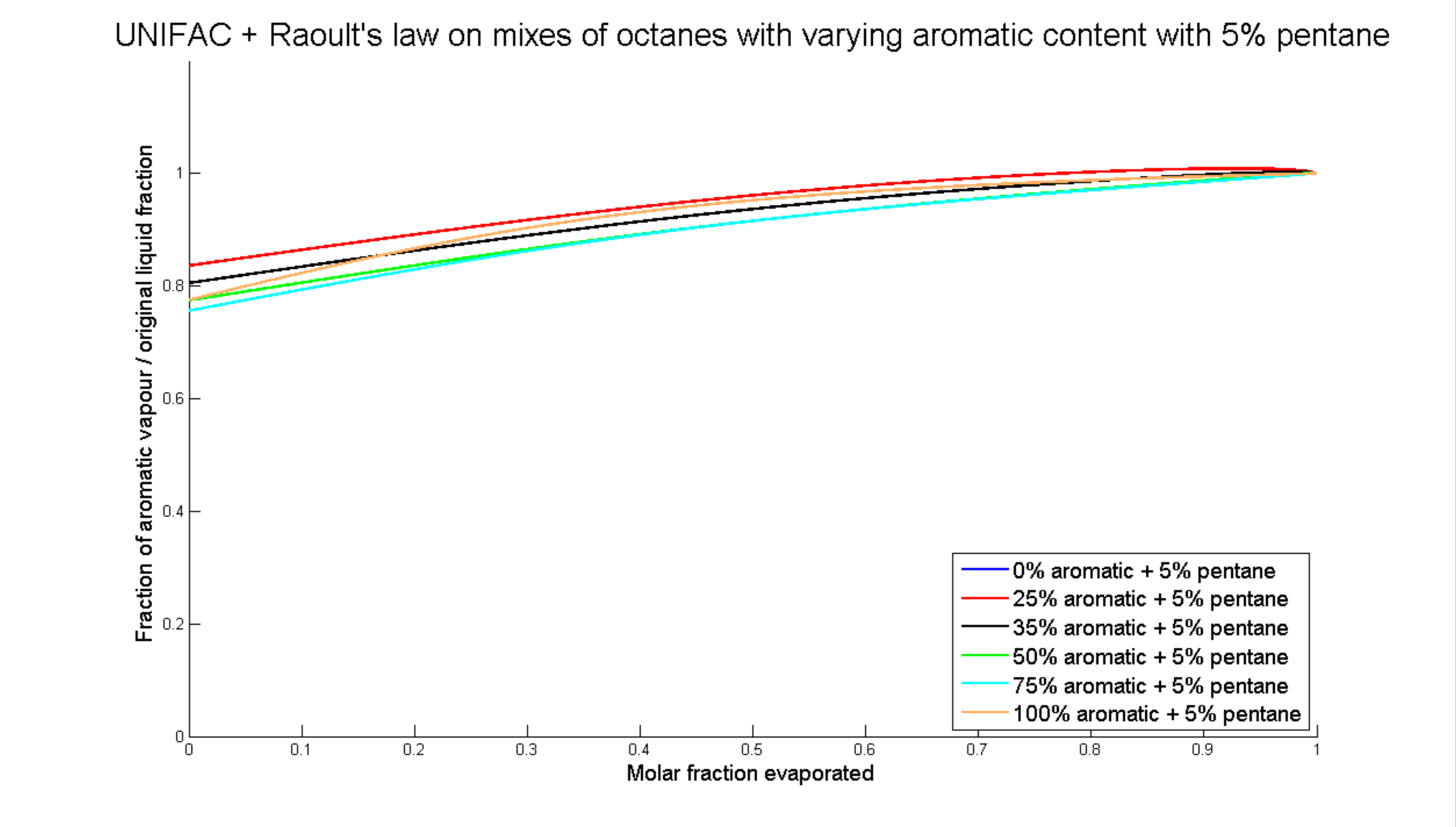
UNIFAC equations (Poling et al 2000)

* Reid, R. C., J. M. Prausnitz, et al. (1987). The properties of gases and liquids. McGraw-Hill.

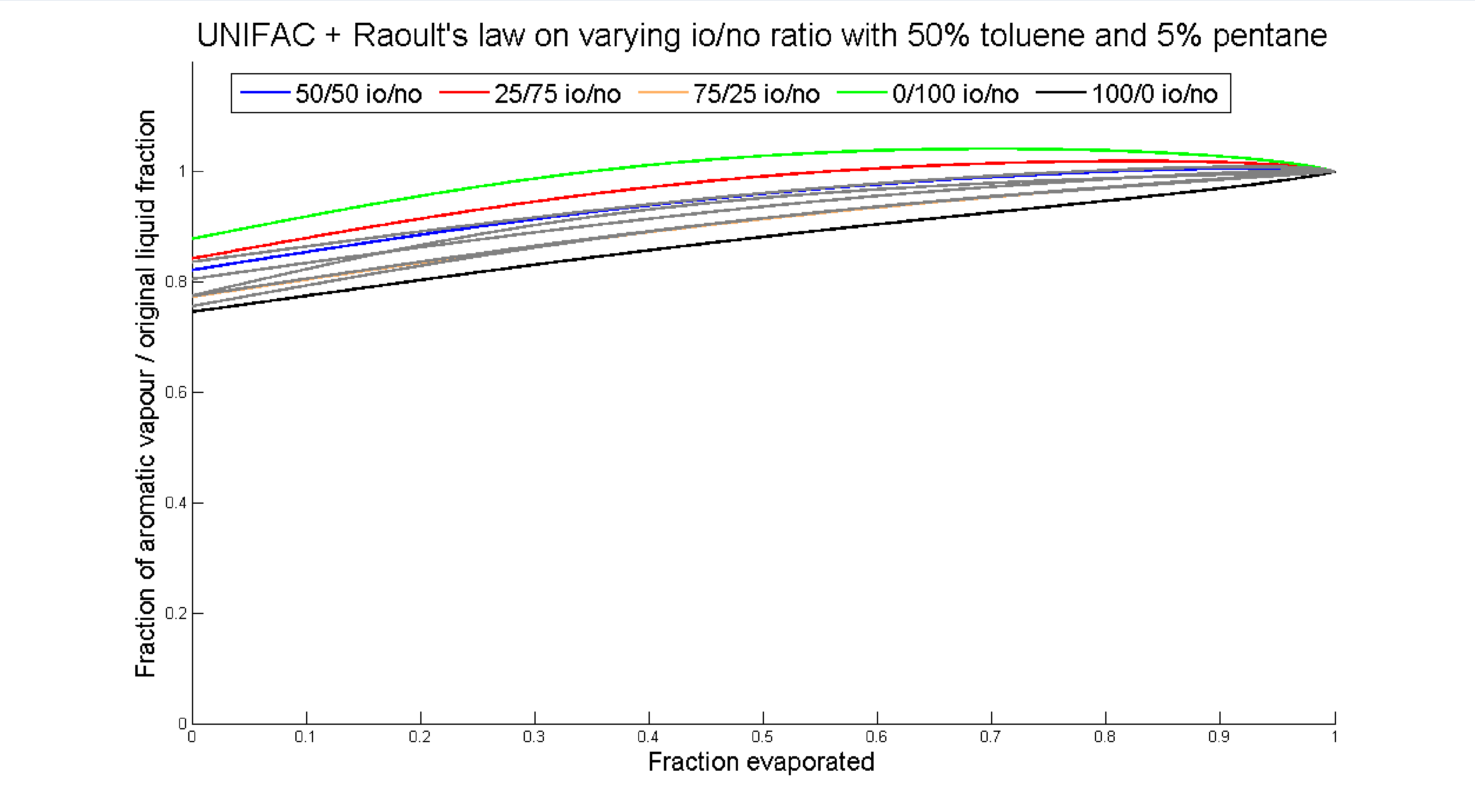
Distillation curve modelling



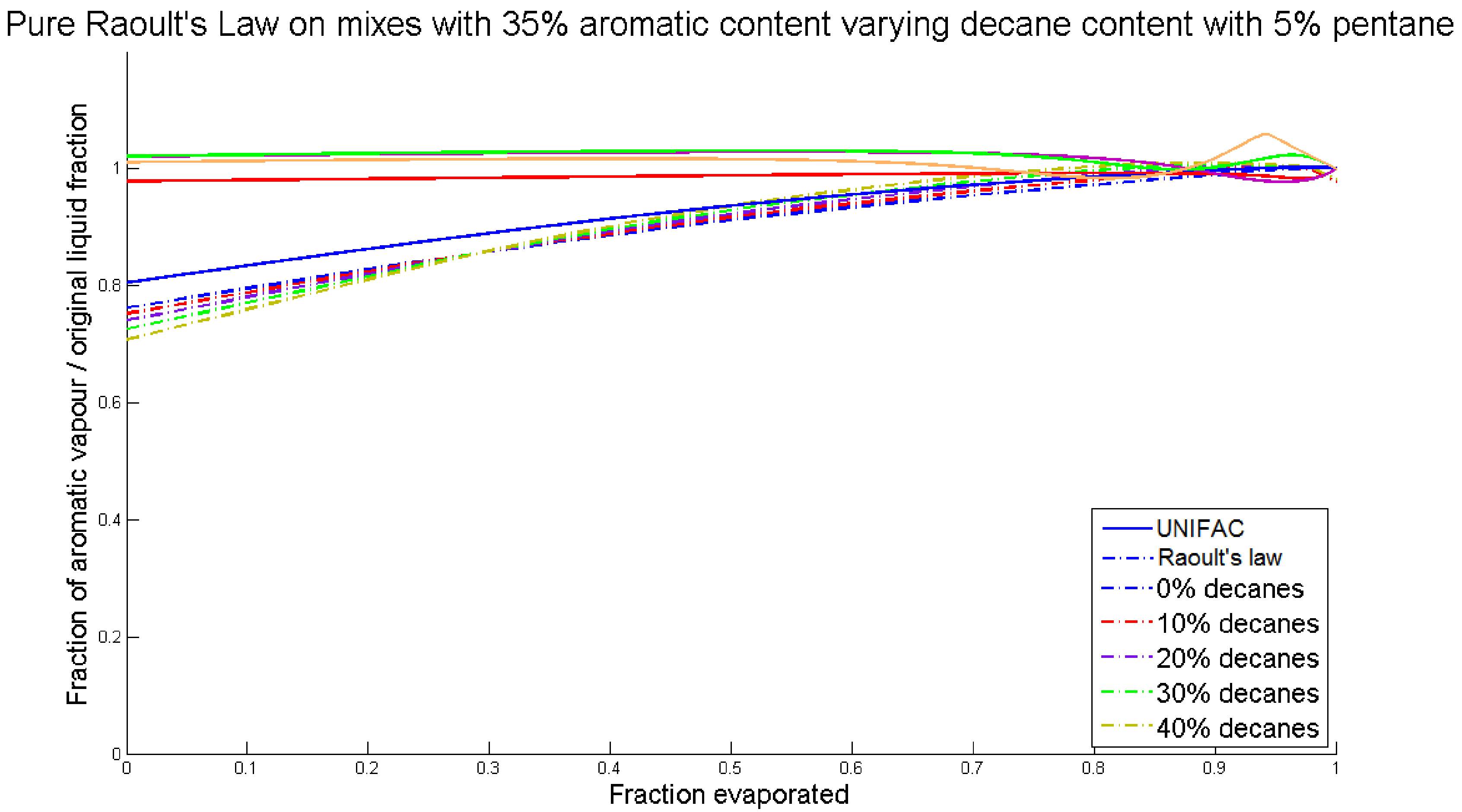
UNIFAC and Raoult's law results



UNIFAC and Raoult's law results



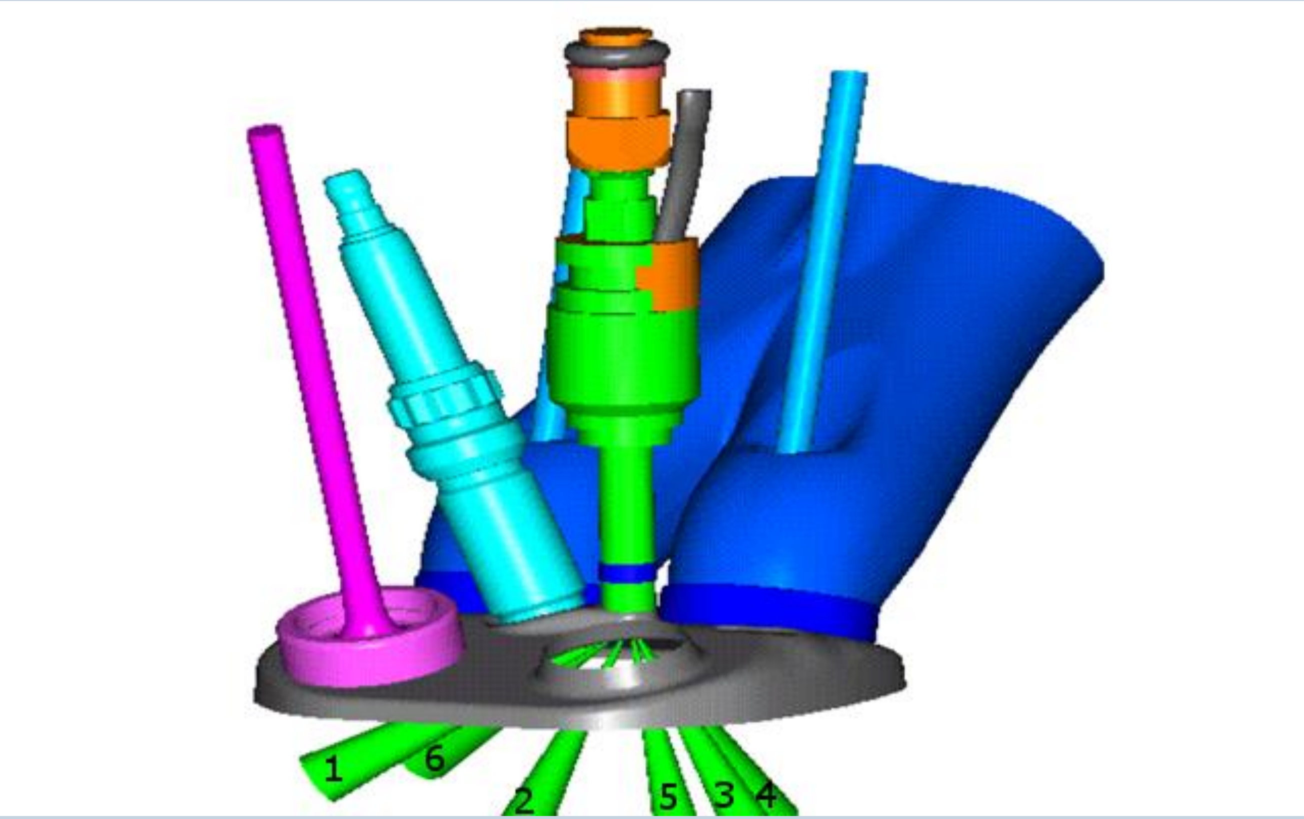
UNIFAC and Raoult's law results



Jaguar AJ-V8 Gen III 5 Litres

- **Naturally Aspirated**
  - **283 kW (380 HP) and 515 Nm,**
  - **Compression Ratio: 11.5:1**
  - **Cam profile switching (CPS)**
  - **Variable geometry inlet manifold**
- **Supercharged Version**
  - **375 kW (503 HP) and 625 Nm**
  - **Compression Ratio: 9.5:1**
  - **Eaton Supercharger**
- **6 hole Bosch Injectors:**
  - **150 bar Injection Pressure**
- **Inlet & Exhaust Variable Cam Timing**
- **Bore 92.5 mm, Stroke 93 mm**

AJV8 Gen 111 Fuel Injection Pattern



Malcolm Sandford, Graham Page and Paul Crawford, SAE 2009-01-1060

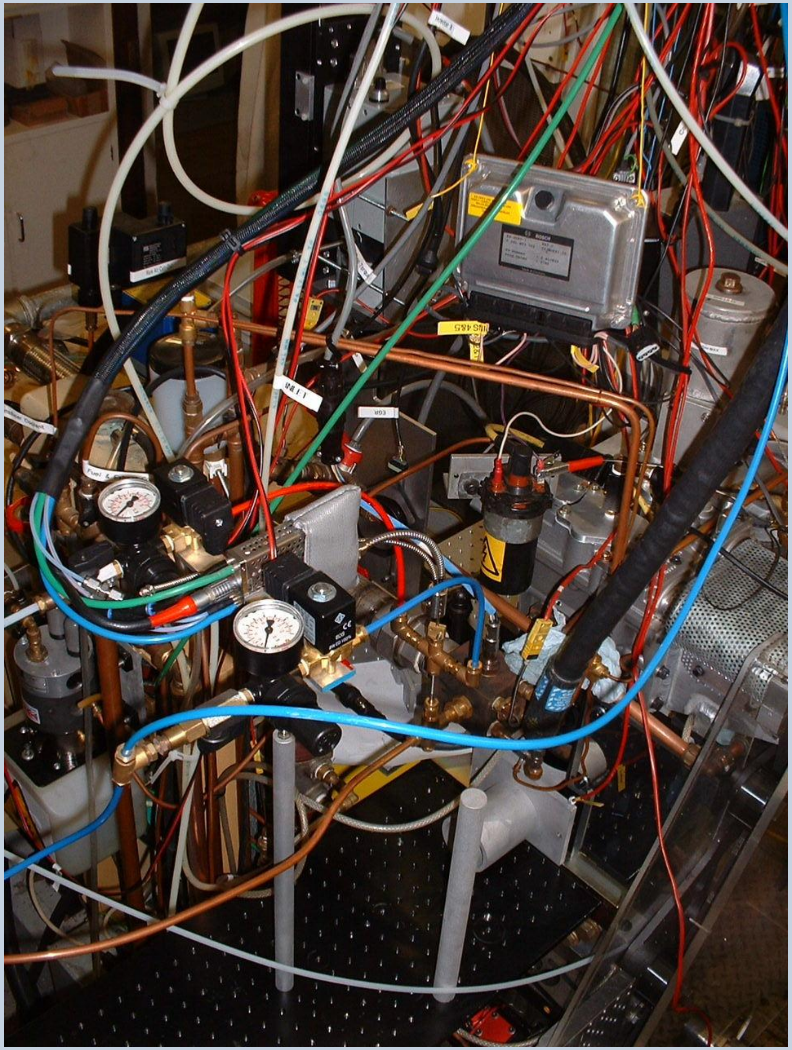
6 Fuel Jets

150 bar injection system

Single Cylinder Engine with Optical Access

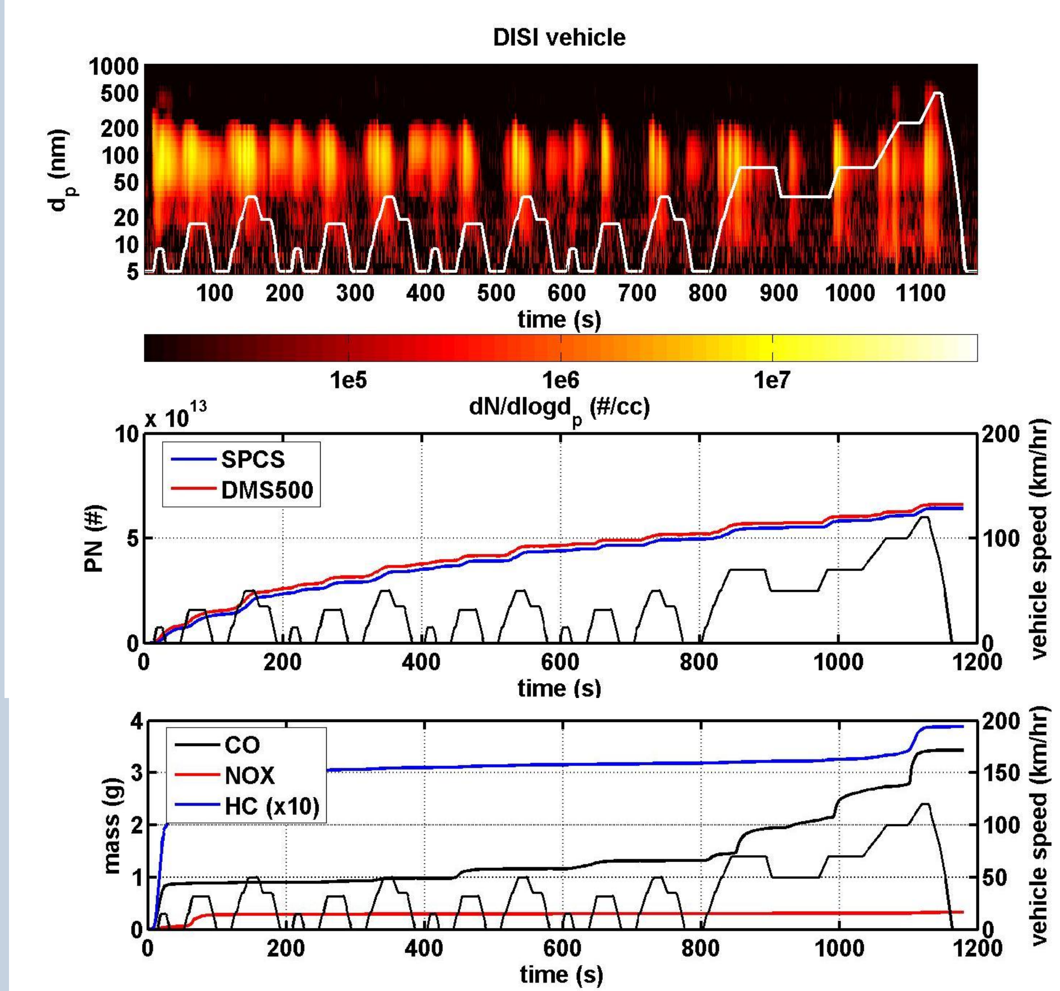
- Bore 89 mm
- Stroke 90 mm
- Capacity 562 cc
- Compression Ratio 11.1
- Injection Pressure 150 bar

- GDI, PFI
- IMEP 1.8bar
- Mixture (air) inlet 40ºC
- Coolant 60ºC
- λ 0.9 and 1.01
- 1500 rpm



Particulate Matter Measurements

- **EUDC**
- **PN Emissions are associated with Transients**
- **Gaseous Emissions are dominated by the Cold-Start**



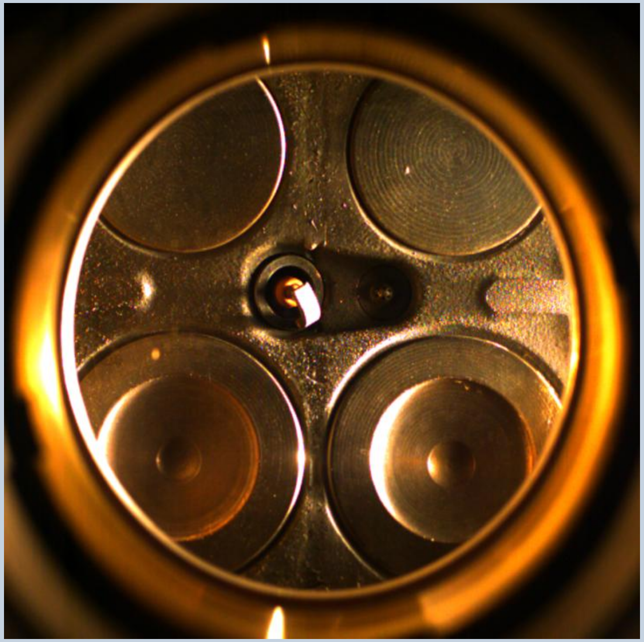
SAE 2010-01-0786

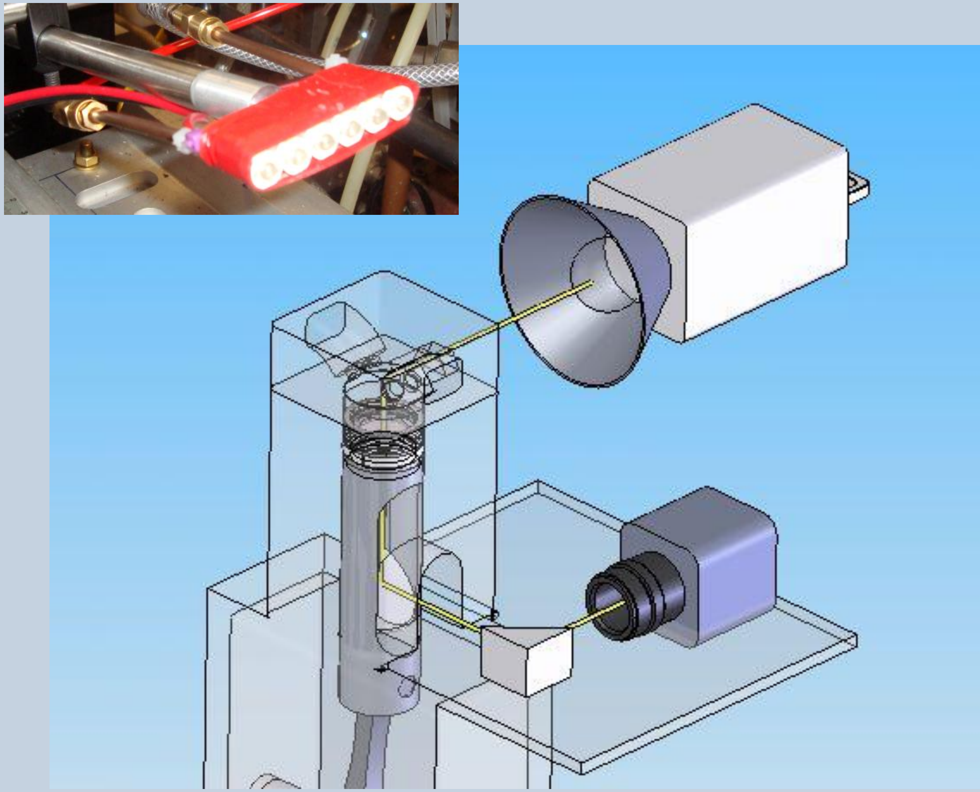
High Speed Imaging – Bowditch Piston

- Photron FASTCAM-1024PCI model

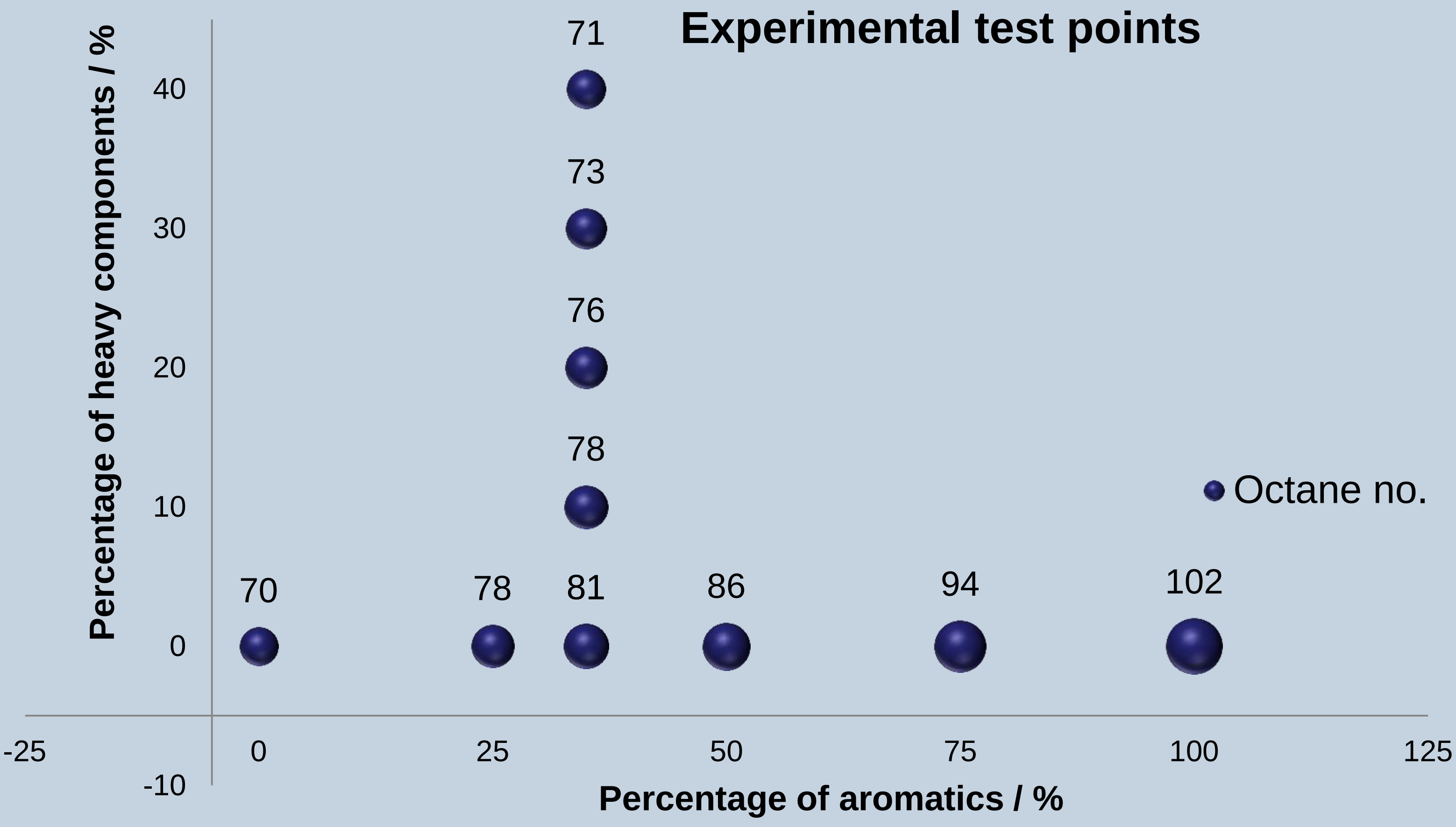
100K Colour Camera – 6000fps

- Resolution: 512 x 256 pixels



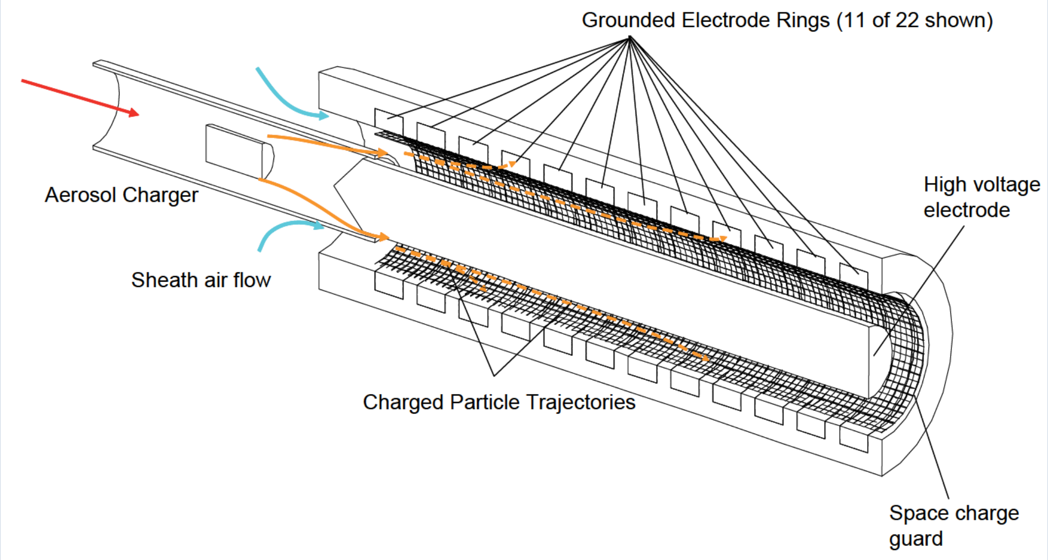


Experimental procedure
Test points

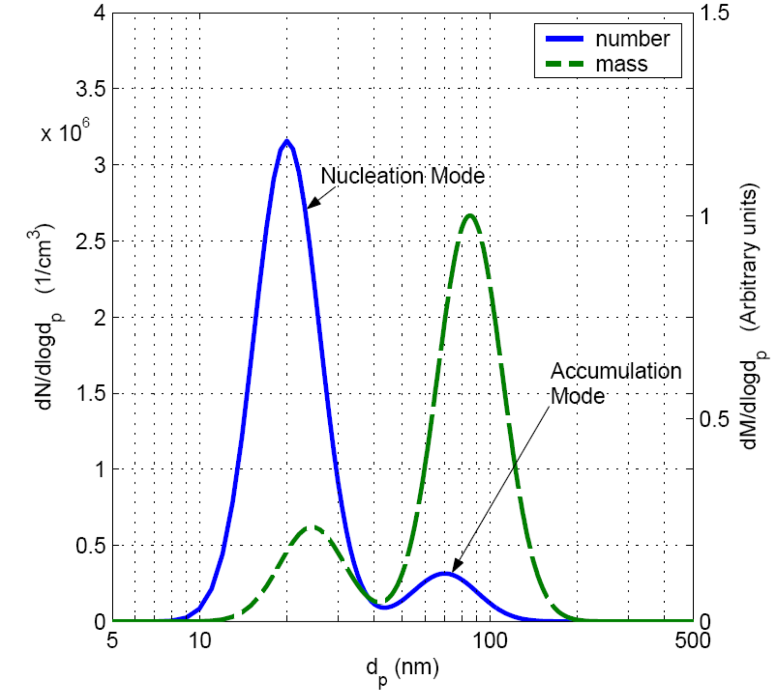


Particulate Matter measurements

Cambustion DMS500



Reavell et al. SAE 2002-01-2714

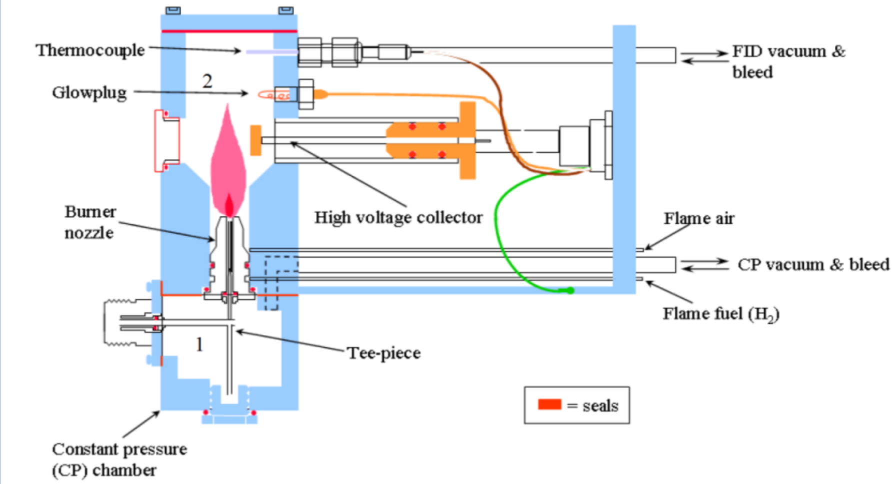


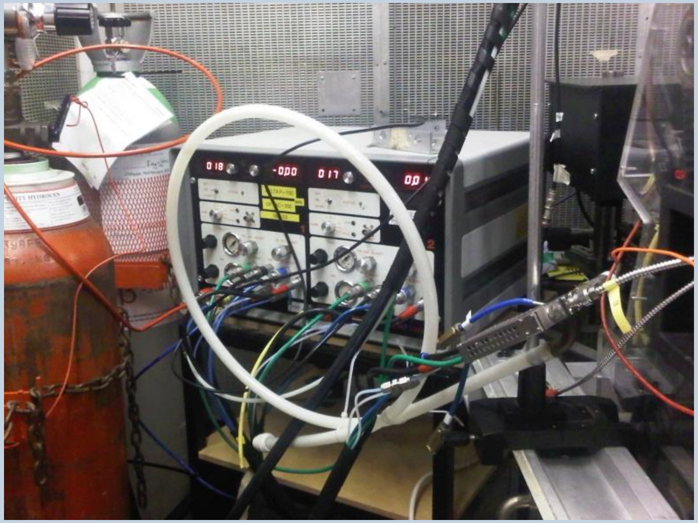
Only accumulation mode used
Replicates PMP measurement protocol
[Braisher et al. SAE 2010-01-0786]

In-cylinder hydrocarbon sampling

Cambustion HFR400 fast FID

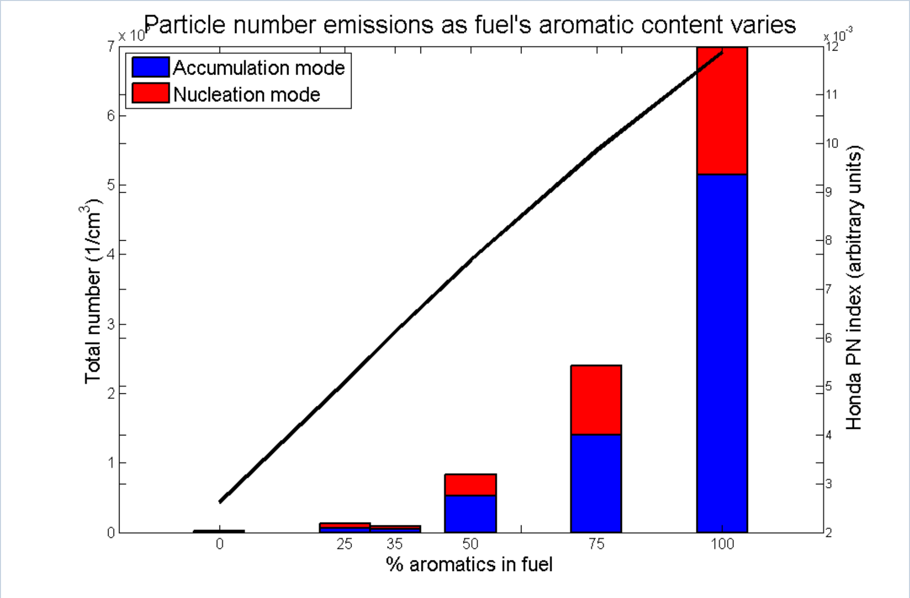
- fFID measures hydrocarbon levels by chemi-ionization
- Response time ~ 4ms



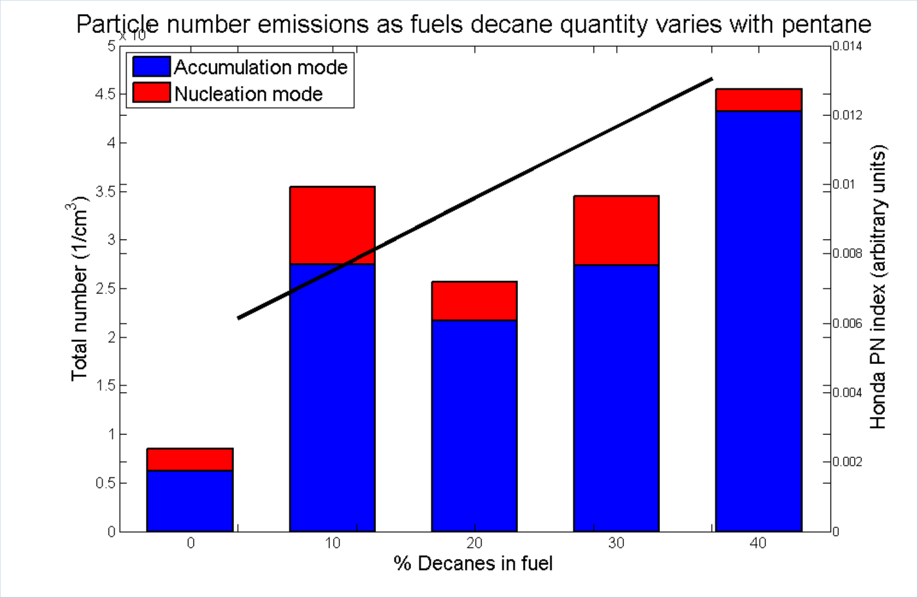


Results

- Clearest trends at λ = 0.9
- Clear agreement with index



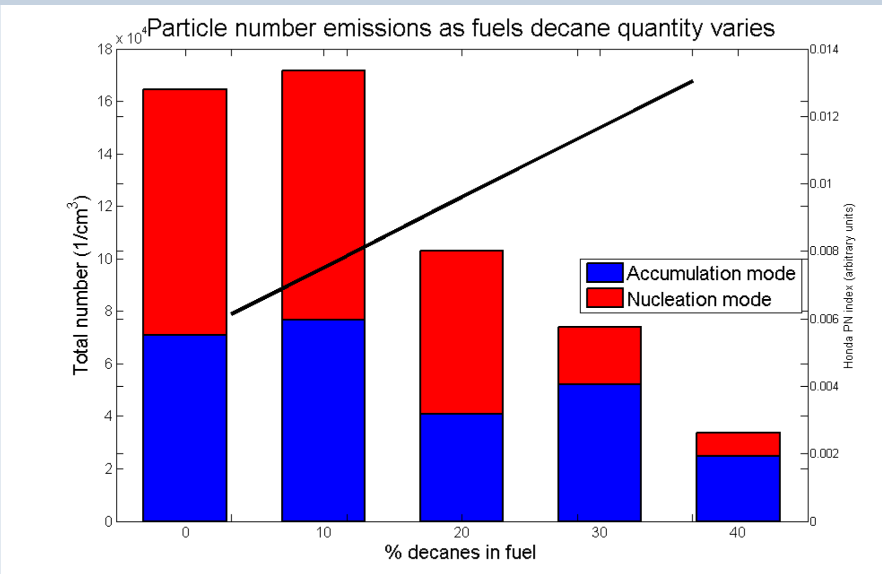
Aromatic sweep λ=0.9



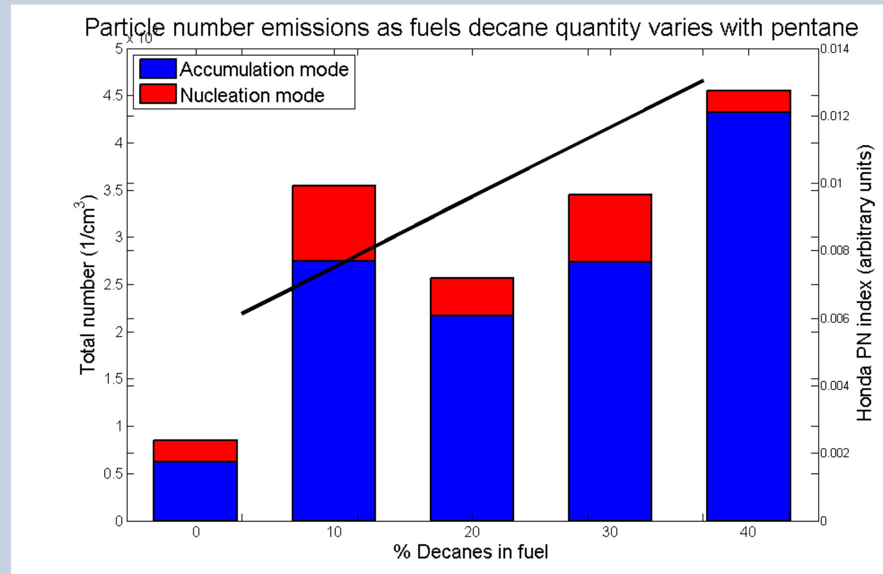
Volatility sweep λ=0.9

Importance of n-pentane

- Much better agreement between volatility sweep and Honda predictions
- Pentane mimics “light end” of commercially available ULG



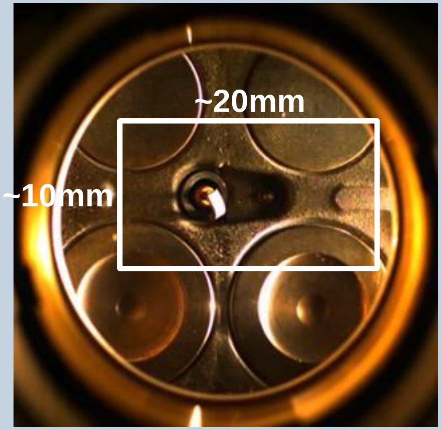
No pentane

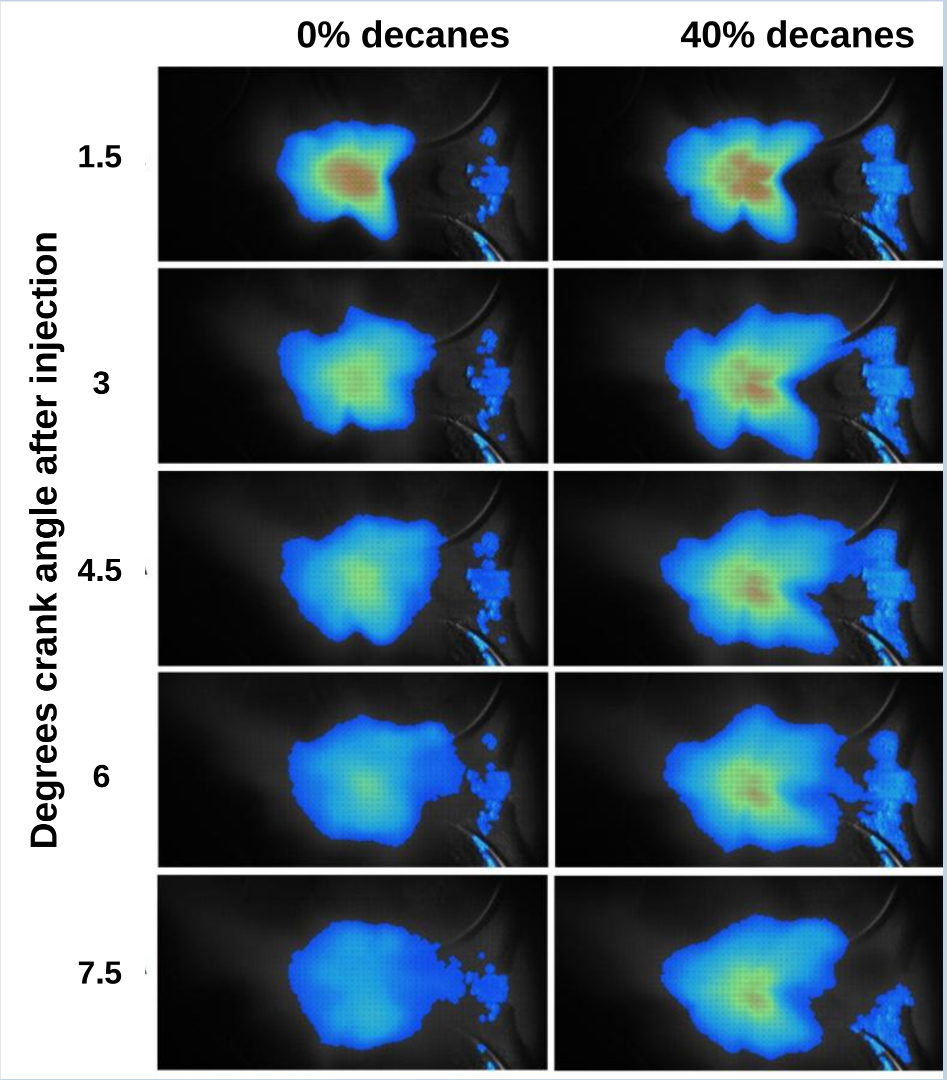


With pentane

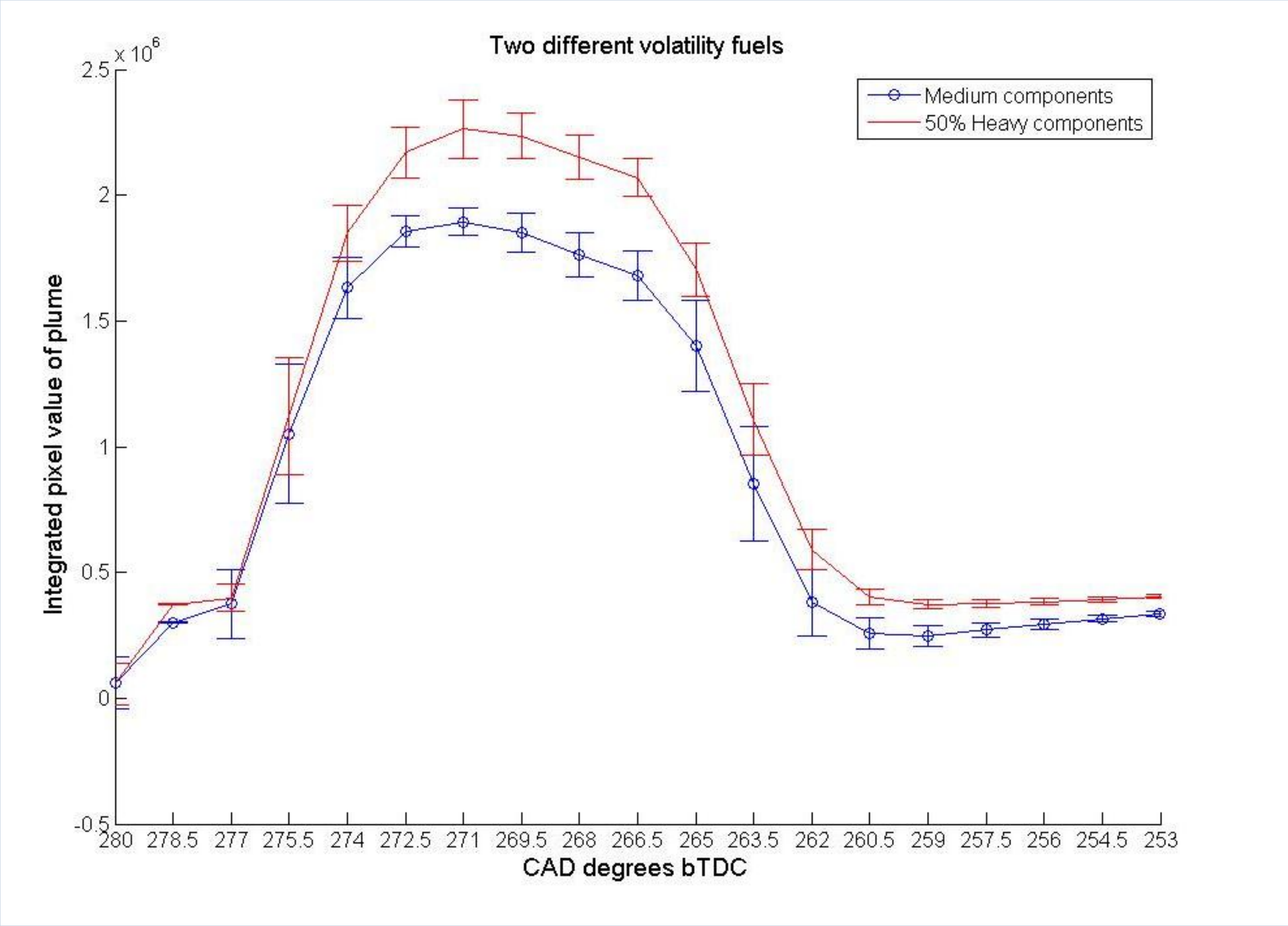
Spray penetration

False colour images

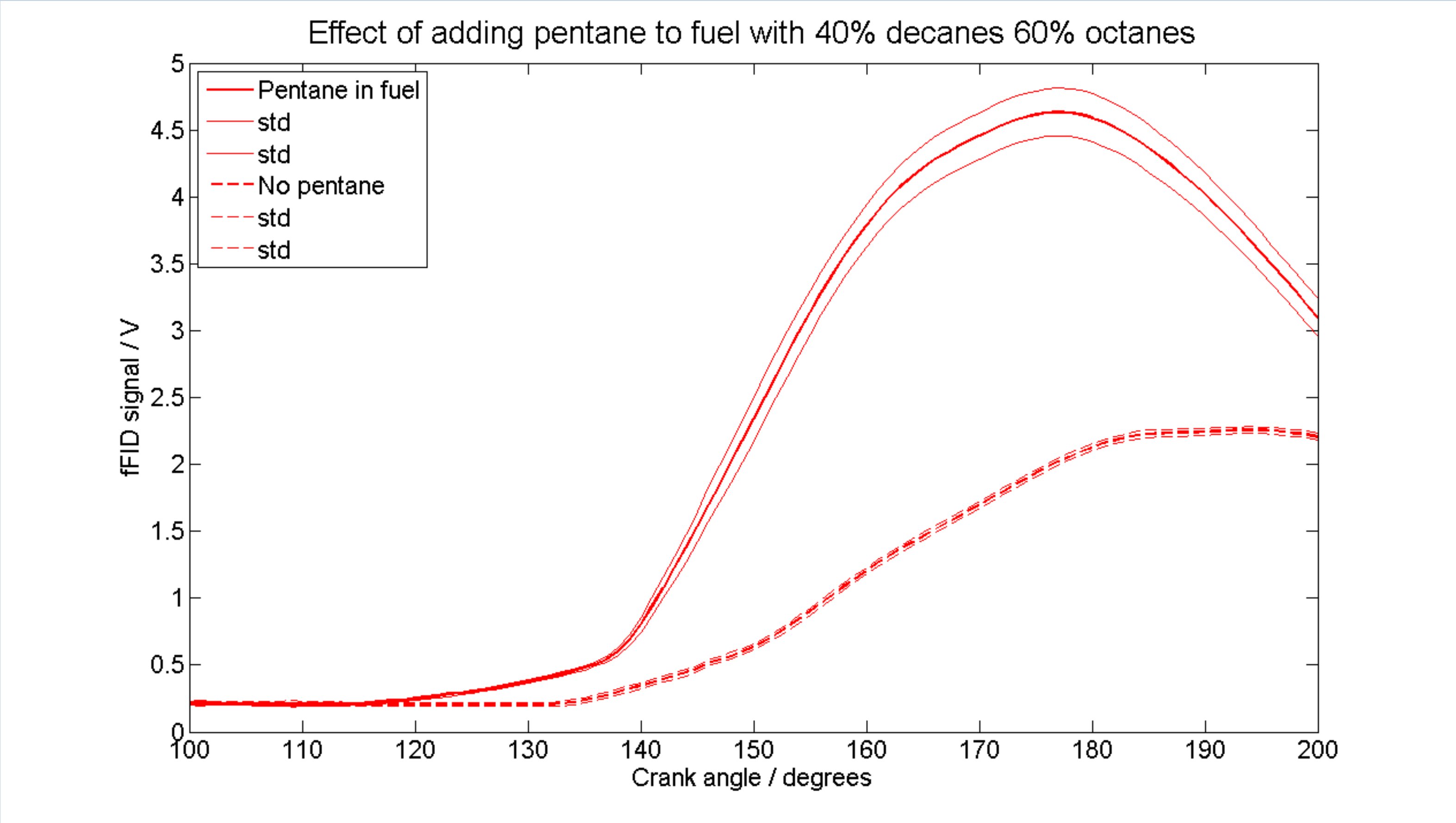




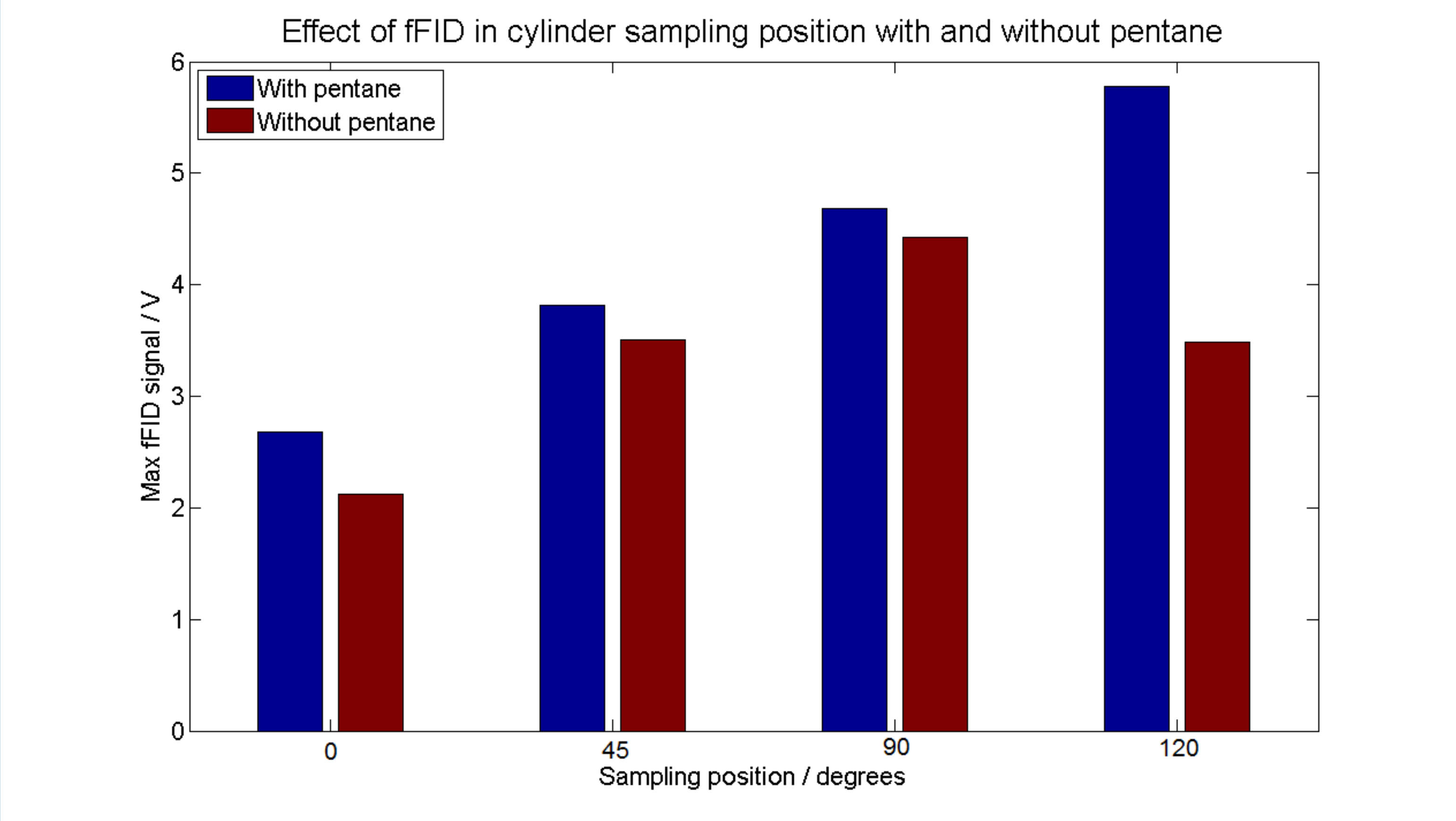
Spray penetration

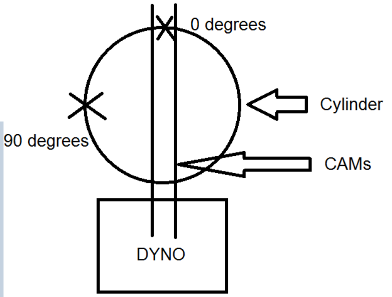


In-cylinder hydrocarbon sampling showing effect of pentane in fuel (40% decanes, 60% octanes)

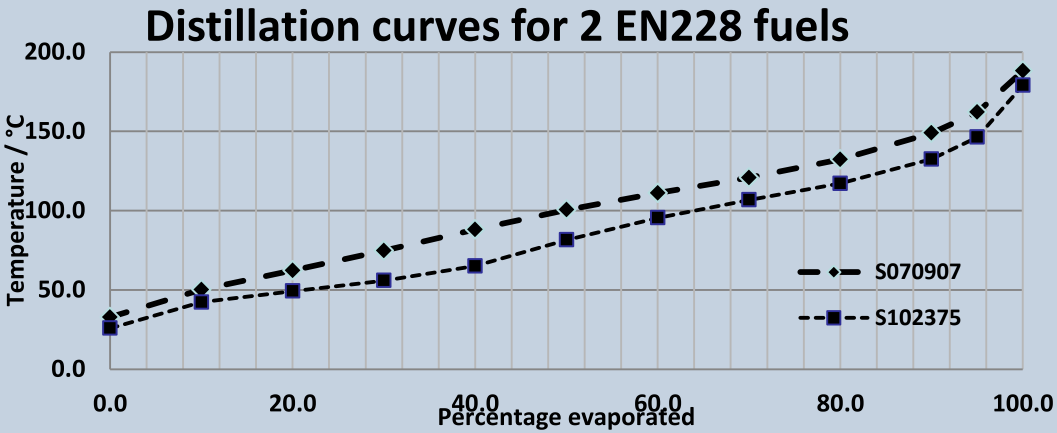


Effect of sampling position



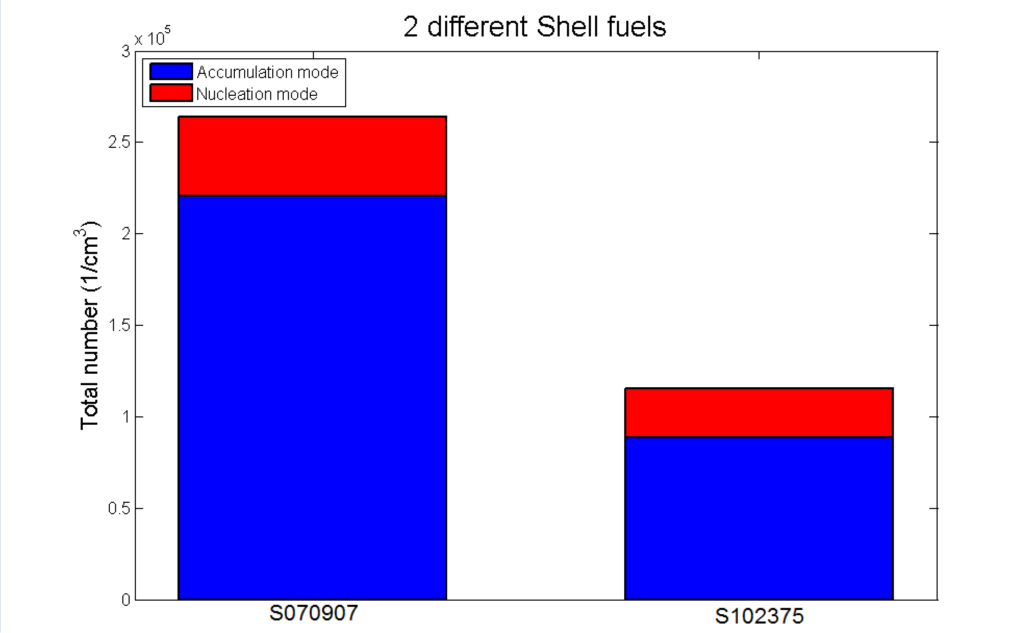


Application to real fuel



	S070907	S102375
RVP* (kPa)	70.6	88.6
DBE	1.58	1.25
FBP (^{0}C)	188.1	179.0
PN Index	1.62e-2	9.77e-3

* Not same method as Honda paper



EU5 Reference Fuel

CEC RF-02-08 fuel specification

	Min	Max
RVP (kPa)	56.0	60.0
Olefins (% v/v)	3.0	13.0
Aromatics (% v/v)	29.0	35.0
Ethanol (% v/v)	4.7	5.3
FBP (^{0}C)	190	210

	EU5 (Min I)	EU5 (Max I)
RVP* (kPa)	60.0	56.0
DBE	2.19	2.53
FBP (^{0}C)	190	210
PN Index	**2.74e-2**	**3.43e-2**

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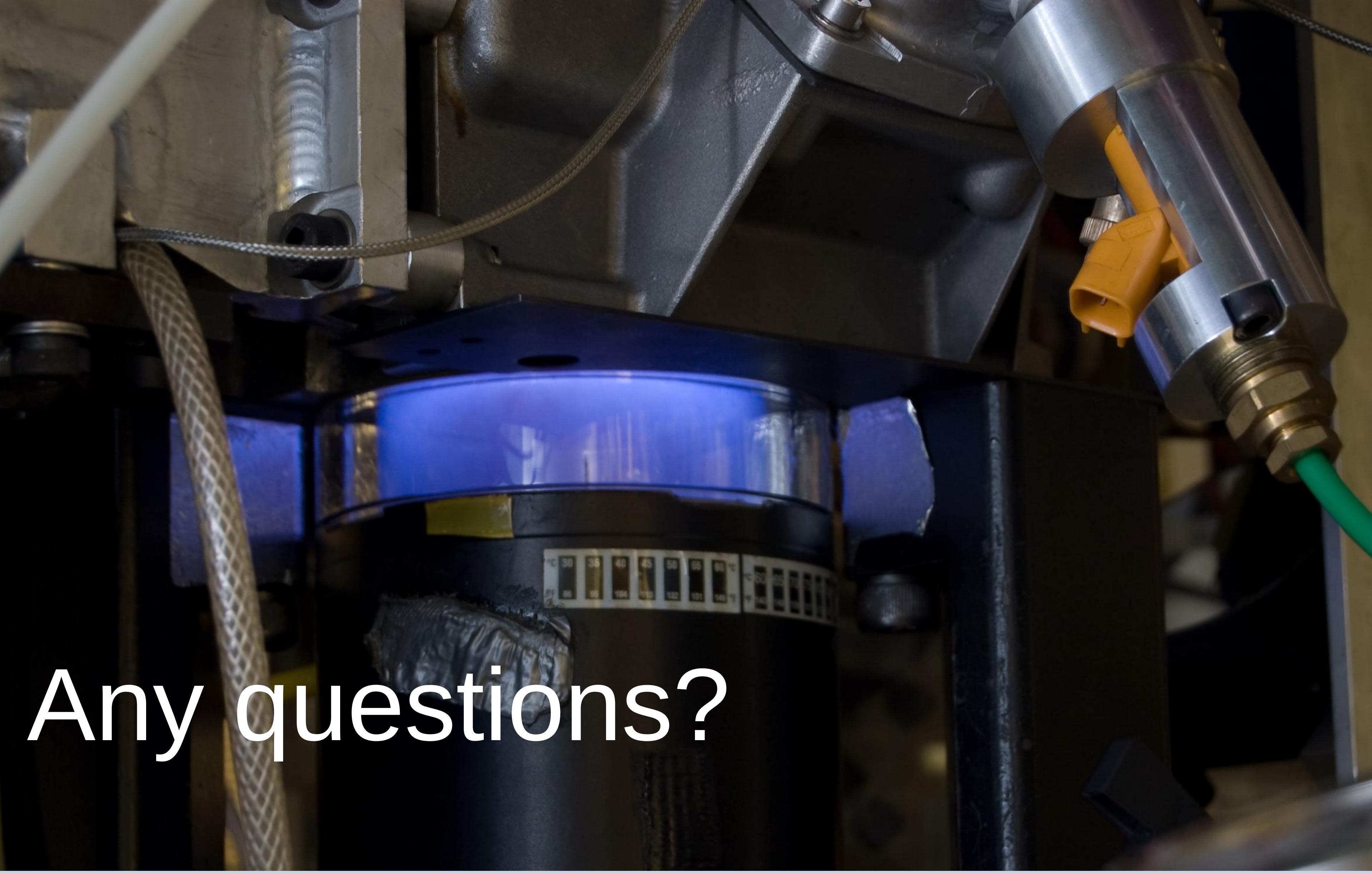
Conclusions

- Fuels blends have been devised that have independent control of volatility and aromatic content
- UNIFAC needs to be used modelling co-evaporation of aromatics
- Effect of light components on Fuel spray is significant
- Trends reported by Honda replicated in SGDI engines using model fuels
- Trends also observed using real fuels in SGDI engine
- Implications for reference fuels



Any questions?

Fuel design

Selection of aromatic components

- Looking for similar boiling points to paraffin components
  - Octanes (~379K), decanes (~444K)
- Aromatics have high RON

	T_b (K), 1.01325 bar	BON*
Benzene	353.2	108
Toluene	383.8	120
1,2,4-Trimethylbenzene	442.5	123
1,3,5-Trimethylbenzene	437.9	161

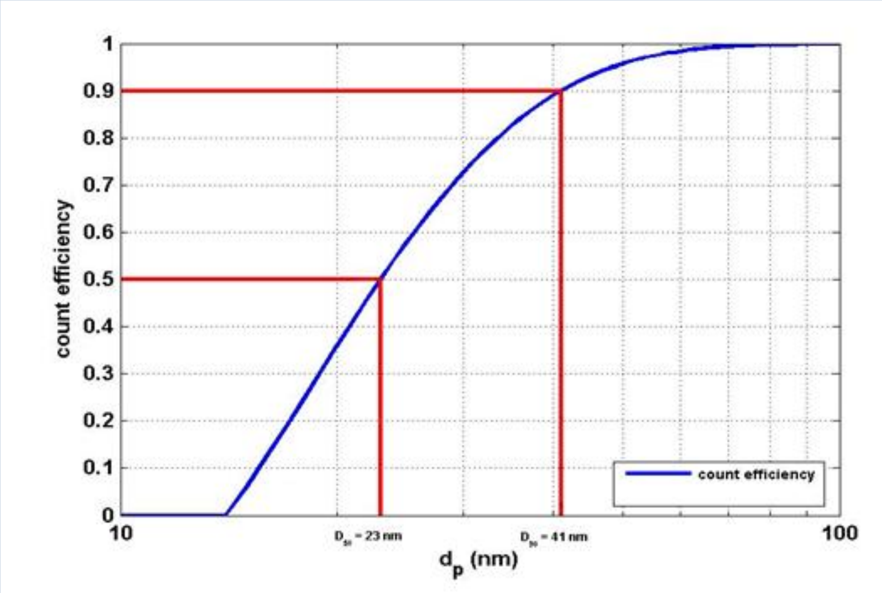
*BON (Blending Octane Number) – equivalent octane number when blended as 20% solution in a 60/40 iso-octane/n-heptane mix. Attempt to give more relevant number than RON when blended with other components. [Lovell 1948]

Digital filtering of low diameter PN

To replicate PMP measurement protocol

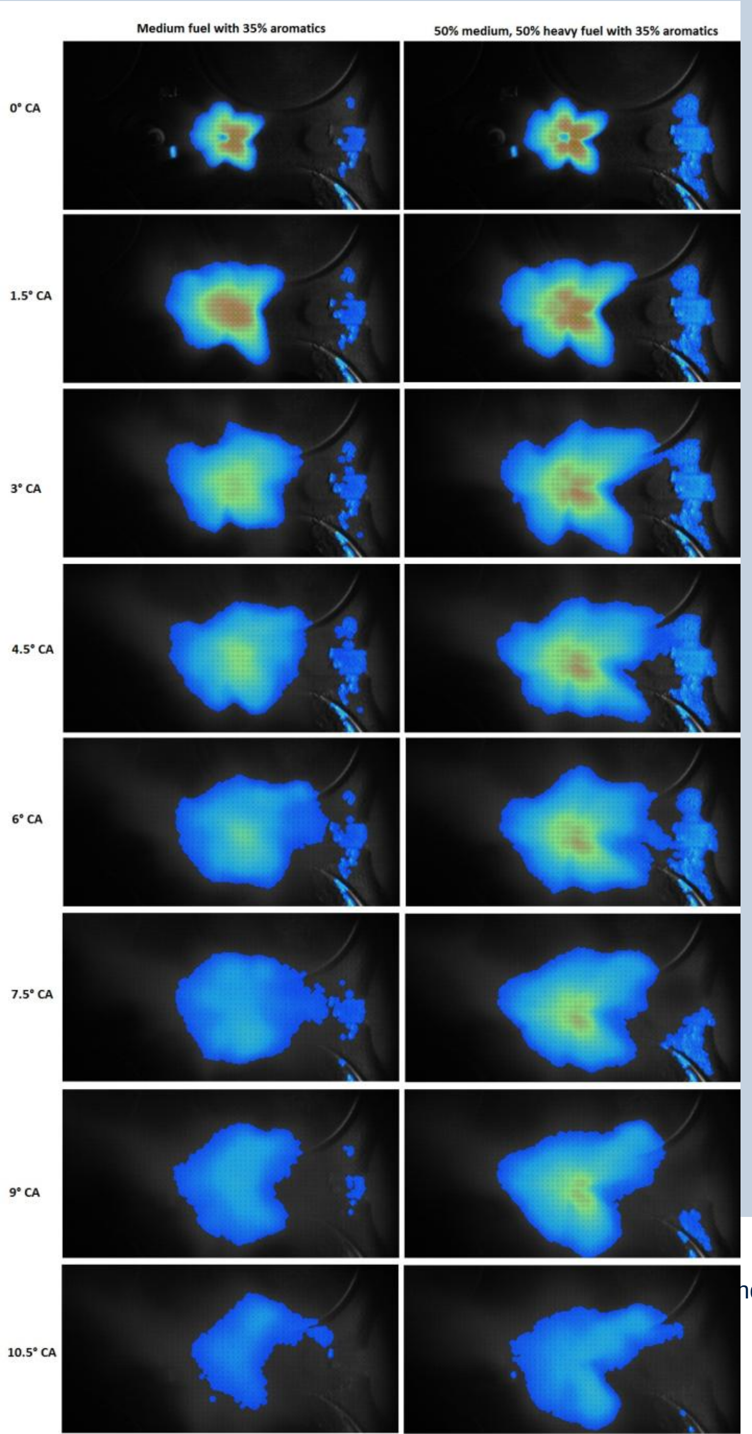
50% count efficiency: D50 = 23 nm

>90% count efficiency: D90 = 41 nm



Wiebe function: $$f = 1 - \exp\left[-3.54\left(\frac{d_p - 14}{40}\right)^{1.09}\right]$$

$d_p > 14$



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