EFFECT OF H_2 ADDITION ON DIESEL ENGINE COMBUSTION AND EMISSIONS

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Outline

- Background
- Experiment methodology
- Engine combustion and emission with H_2 addition
- Physiochemical properties of DPM
- Morphology of DPM
- Unregulated emissions

Background

- Increasing stringent emission legislation (Euro V, VI)
- Heavy dependent on after treatment devices: selective catalytic reaction (SCR), diesel particulate filter (DPF), et al. (precious metal)
- Cost-effectiveness for retrofitting engine (maintenance)
- Dual-fuel diesel engine as a compromising strategy (non-soot gas)
- Biodiesel fueled diesel engine
- Conventional dual-fuel engine
- Diesel-natural gas (NG) (Sichuan, China)

Background

- **Drawbacks of conventional dual-fuel C.I. engine**

  For example, Diesel-LPG & Diesel-NG

- Secondary pollution: unburned CH_4, C_3H_8, C_4H_{10}, CO et al.
- Higher NOx emission at higher loads
- Lower thermal efficiency at lower loads
- Dependent on fossil fuel (LPG)

- **Diesel (Biodiesel)-Hydrogen??**

Background

- **Hydrogen fuel properties**

➢ Carbon-free H-H >> non-soot

➢ High flame propagation speed 170 cm/s >> fast burning rate

➢ High diffusivity 0.61 cm^2/s >> homogenous mixture

➢ High heating value LHV=119.93 MJ/kg >> high power

➢ High Octane number RON>120 >> high compression ratio

➢ High auto-ignition temperature 858K >> high CR

➢ Wide flammability limits 4~75% in air >> ultra lean burn

➢ Low ignition energy 0.02 mJ >> backfire, pre-ignition

➢ Small quenching distance 0.64mm >> surface ignition

White et al. Int J Hydrogen Energ. (2006); Szwaja and Grab-Rogalinski. Int J Hydrogen Energ. (2009)

Background

- **Hydrogen combustion modes**
  - Mode 1:Hydrogen assisted combustion
  - Mode 2:Hydrogen dual-fuel combustion
  - Mode 3:Hydrogen direct injection and combustion

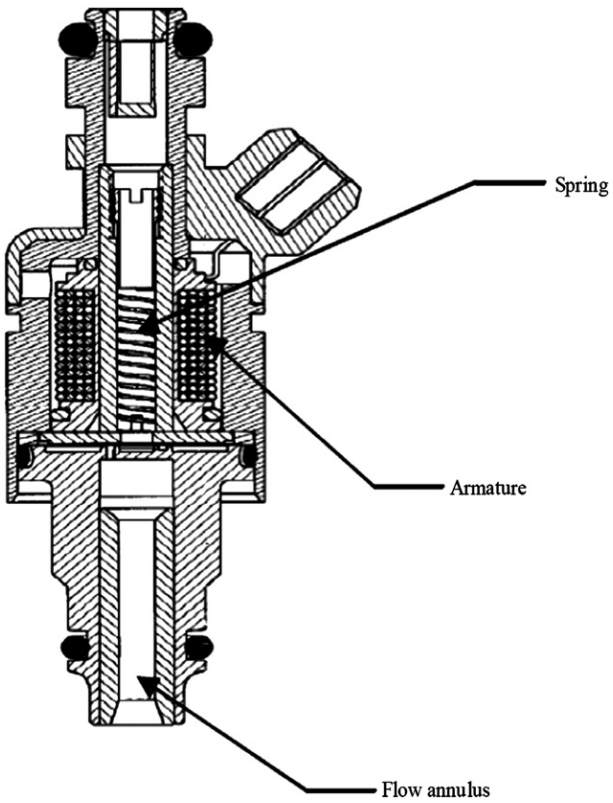
Roy et al. Int J Hydrogen Energ. (2010).

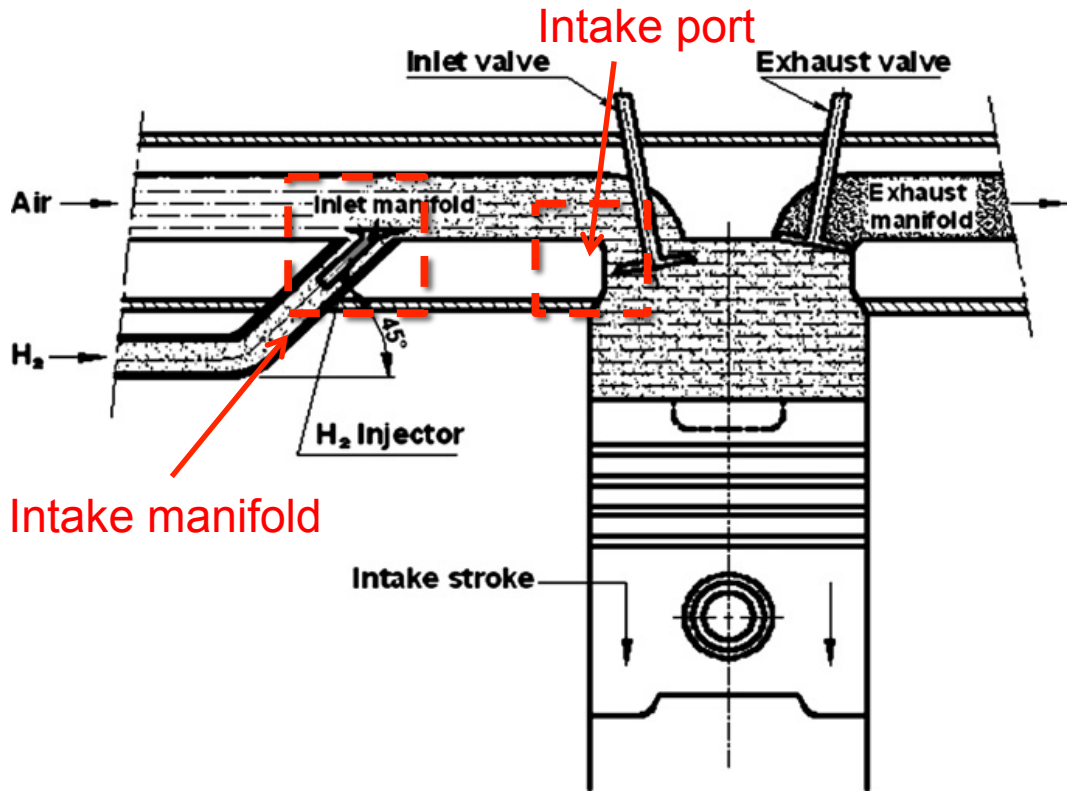
- **Hydrogen supplementation methods**
  - Intake port aspiration (Mode 1, mode2)
  - Intake port/manifold injection (Mode 1, mode 2)
  - Direct injection (Mode 3, liquefied hydrogen)

Saravanan et al. Int J Energ Res; (2009);Saravanan et al. Energy & Fuels. (2009); Saravanan et al. Int J Hydrogen Energ. (2007); Miyamoto et al. Int J Hydrogen Energ. (2011).

Background

- **Intake manifold/port injection**

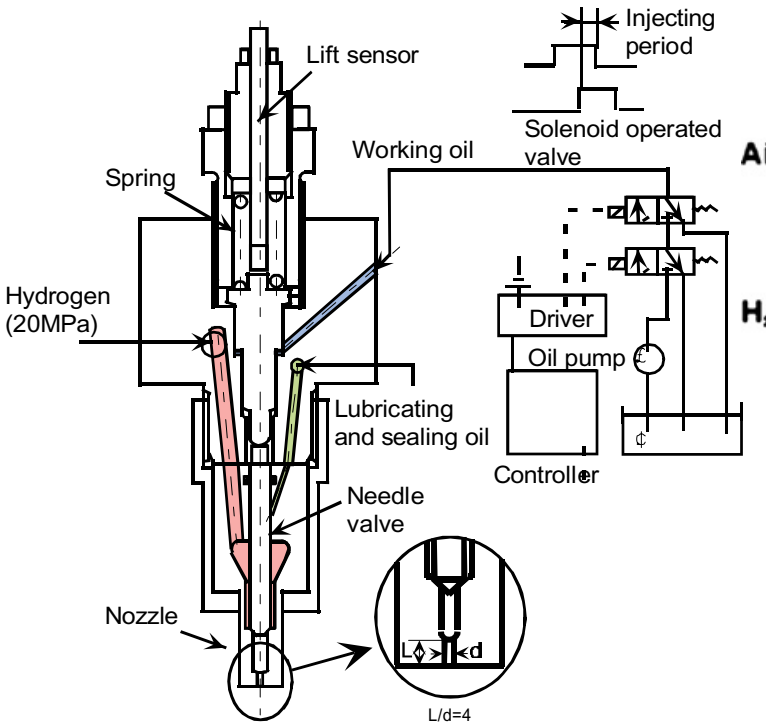


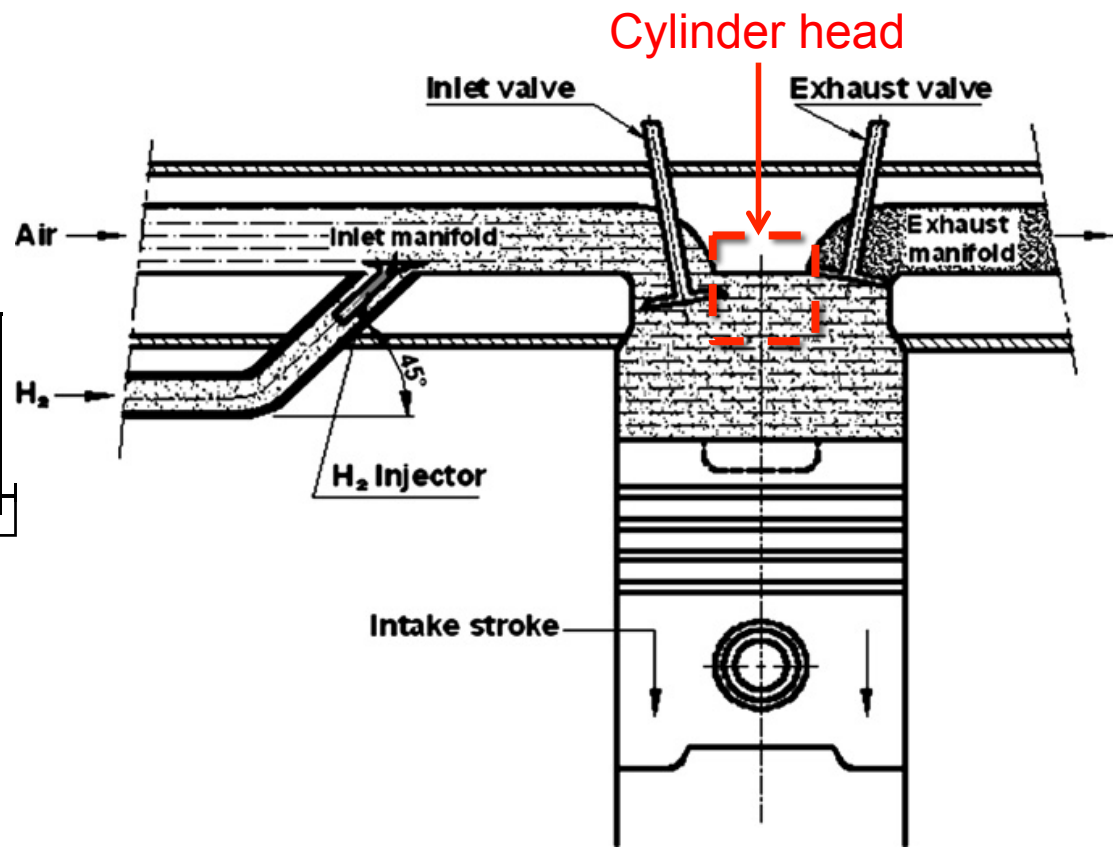


Saravanan et al. Int J Energ Res; (2009)

Background

- **Direct injection**





Hiroyuki et al. SAE paper, 1999-01-2521

Background

- **Hydrogen supplementation methods**
  - Intake port aspiration (Mode 1, mode2)
  - Intake port/manifold injection (Mode 1, mode 2)
  - Direct injection (Mode 3)

Table 3
Theoretical power densities of hydrogen-, methane- and iso-octane-fueled engines.

	Hydrogen	Methane	Iso-octane
PFI	86%	92%	100%
DI	119%	100%	100%

Verhelst and Wallner. Progress in Energy and Combustion Science. (2009)

Background

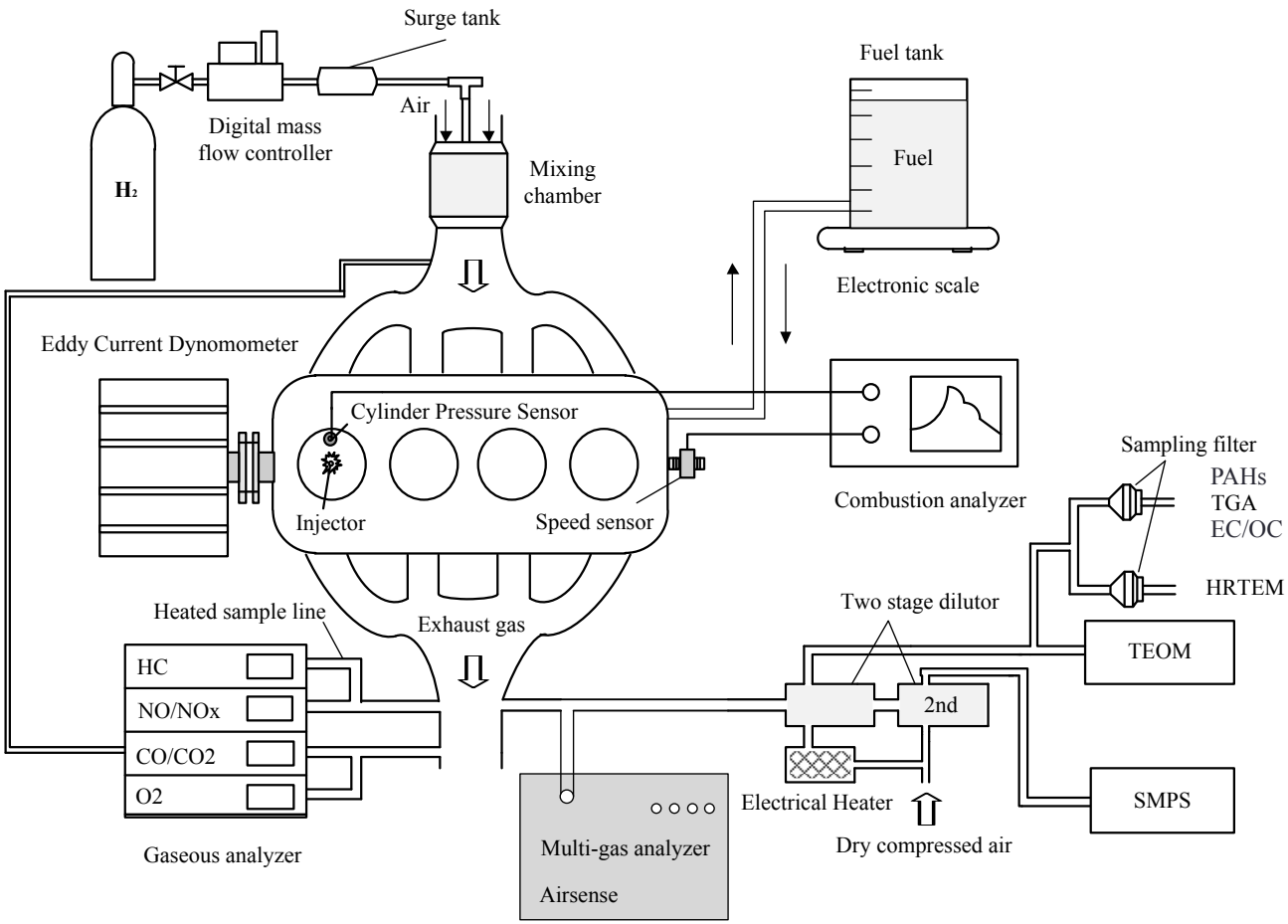
- **Limitations**
- Lack of study of the effect of hydrogen on the physiochemical properties of particulate

- Lack of study of the effect of hydrogen on unregulated gaseous emission
  - Both PM and unregulated emission are extremely toxic
  - Detailed characterization of PM is necessary for a better understanding of hydrogen dual-fuel combustion process

- Lack of study of the effect of hydrogen on diesel engine fueled with biodiesel and biodiesel-diesel blends
  - Biodiesel contains less polycyclic and aromatic compounds
  - Biodiesel has the potential to reduce both PM and unregulated emissions

Experimental methodology

- **Experimental apparatus**



Experimental methodology

- **Experimental apparatus**

Parameters	Instruments & Manufactory
Cylinder pressure	Piezoelectric sensor, Kistler Inc.
Total HC	HFID, CAI Inc.
NO/NO_x	HCLA, CAI Inc.
CO/CO_2	NDIR, CAI Inc.
Smoke opacity	Diesel tune smoke-meter, SPX DX.210
Particle mass	TEOM, Rupprecht&Patashnick Co., Inc.
Particle number	SMPS, TSI Inc.
Hydrogen flow control	Digital mass flow controller, Alicat Co. Inc.
Unregulated gas	IMR-GS, Airsense Inc.

Experimental methodology

- **Useful expressions**

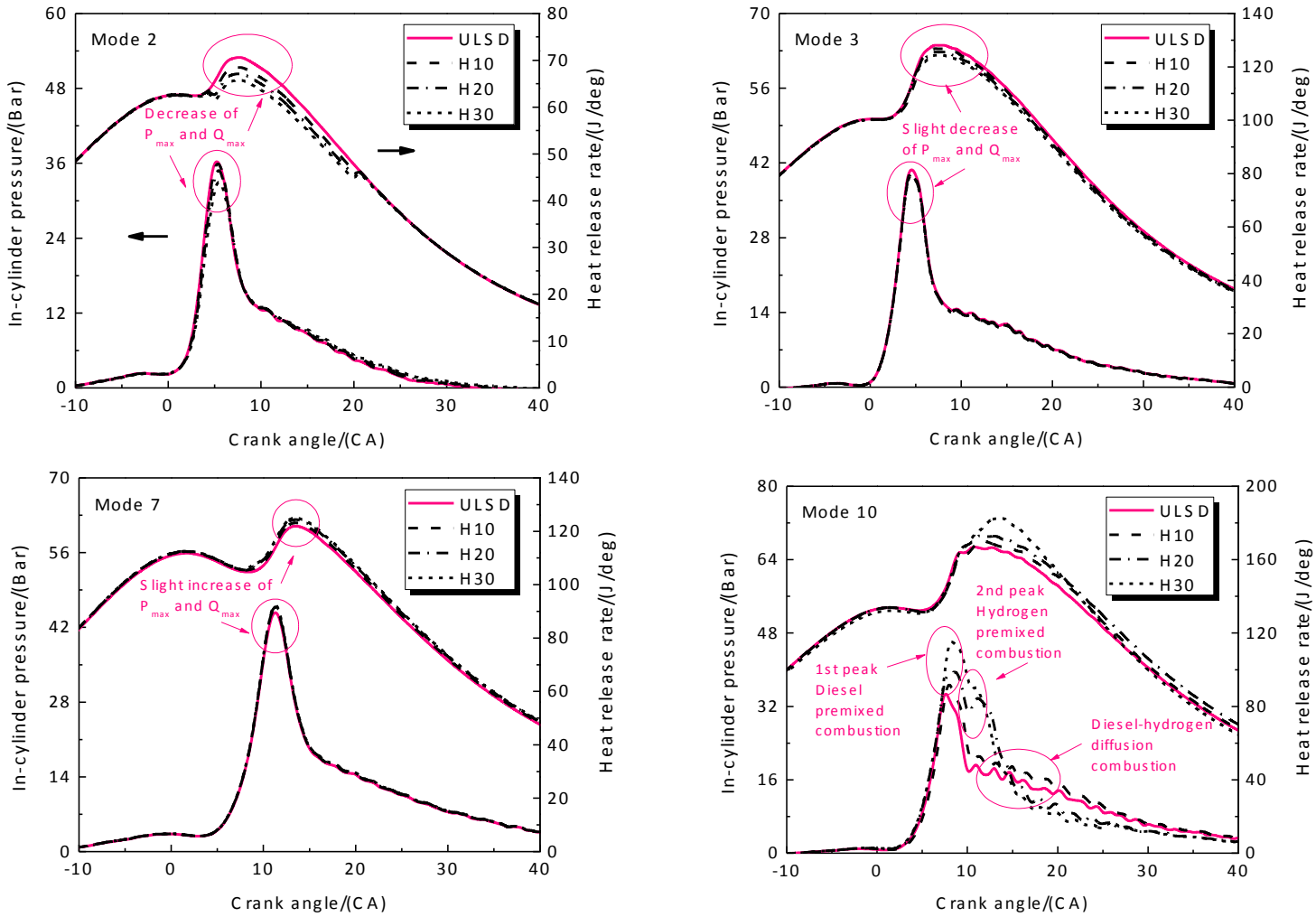
$$H_2 \text{ energy substitutin ratio} = \frac{\dot{m}_{H2} \cdot LHV_{H2}}{\dot{m}_{fuel} \cdot LHV_{fuel} + \dot{m}_{H2} \cdot LHV_{H2}} \quad (1)$$

$$BSFC = \left[\dot{m}_{fuel} + \boxed{\left(LHV_{H2}/LHV_{fuel}\right) \times \dot{m}_{H2}}\right] / \left(T \cdot 2\pi\pi\right) \quad (2)$$

$$BTE = \frac{T \cdot 2\pi\pi}{\dot{m}_{fuel} \cdot LHV_{fuel} + \boxed{\dot{m}_{H2} \cdot LHV_{H2}}} \quad (3)$$

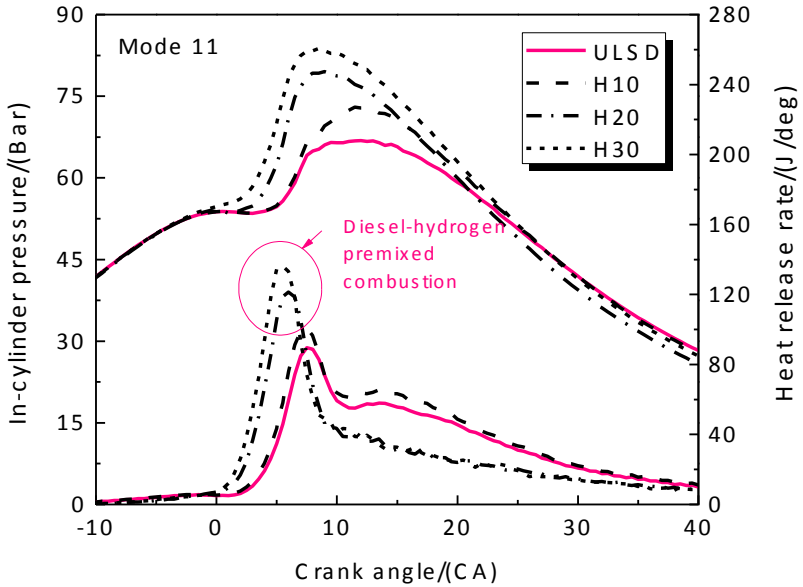
Where, $\dot{m}_{H2}$ and $\dot{m}_{fuel}$ are the mass flow rates of hydrogen and liquid fuel, in kg/h; LHV_{H2} and LHV_{fuel} are the lower heating value of hydrogen and liquid fuel, in MJ/kg, respectively; T is the engine torque, in Nm; n is the engine speed in rev min^{-1}

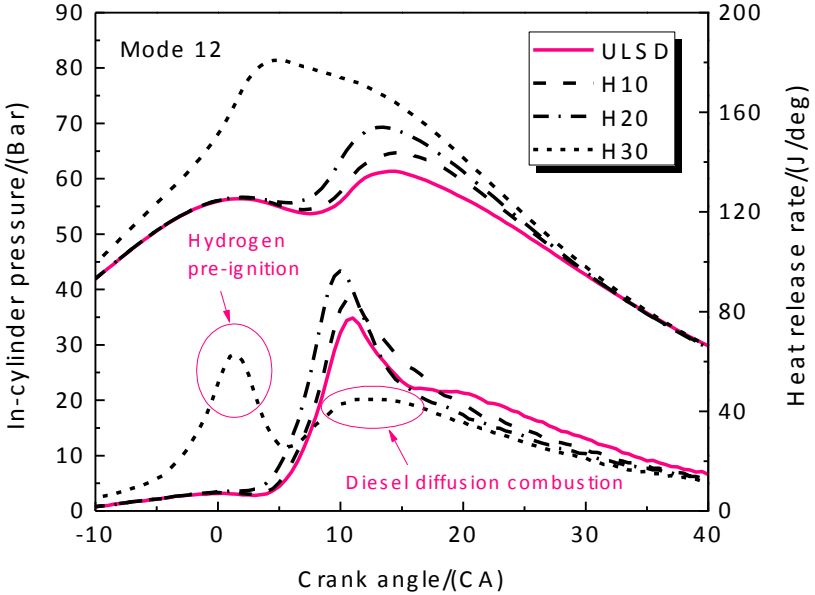
Engine combustion and emission with H_2 addition



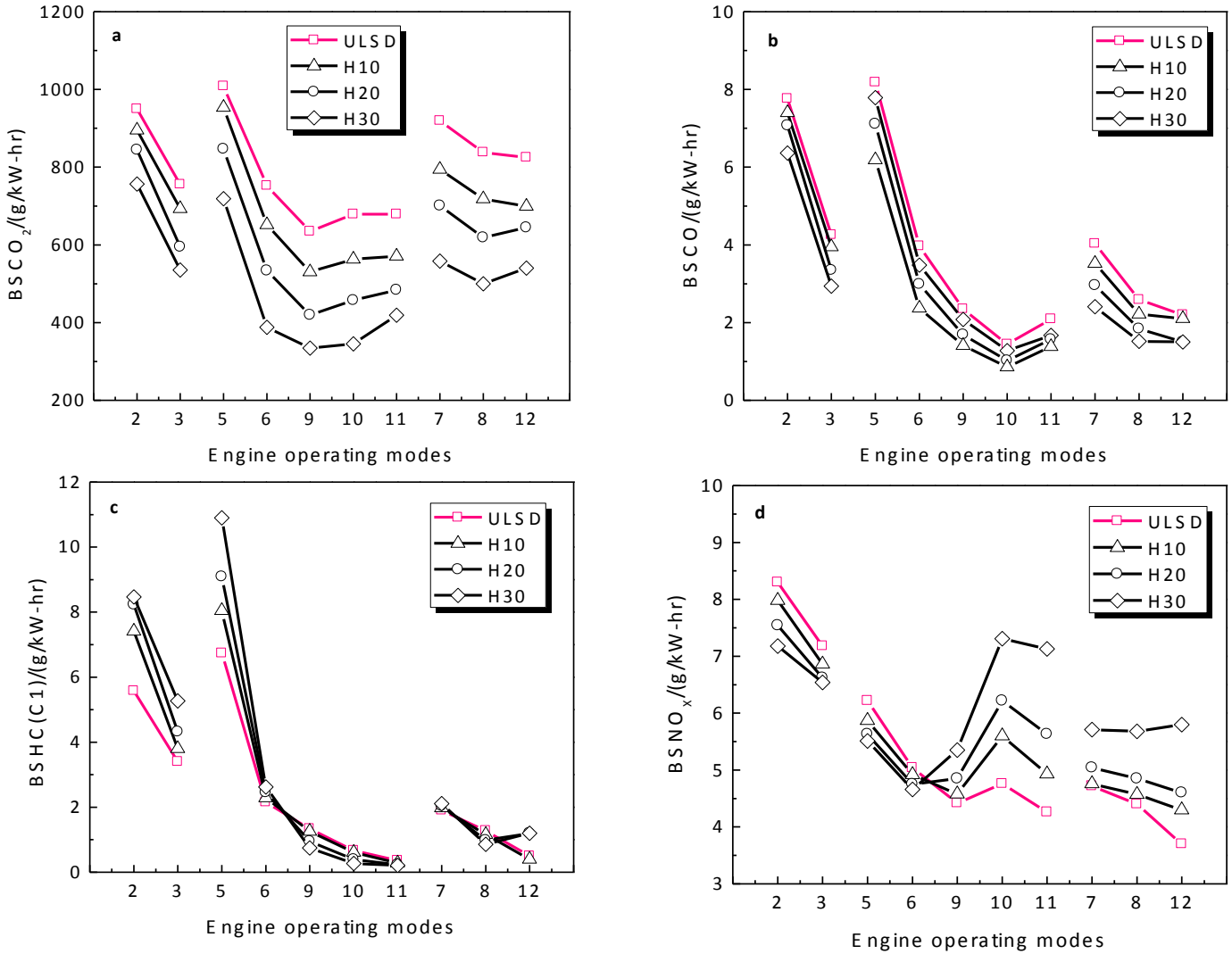
Engine combustion and emission with H_2 addition

Abnormal combustion



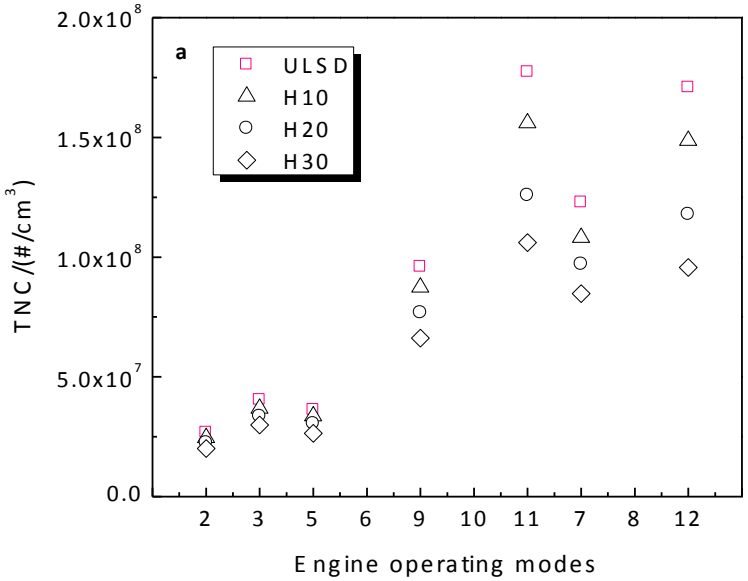


Engine combustion and emission with H_2 addition

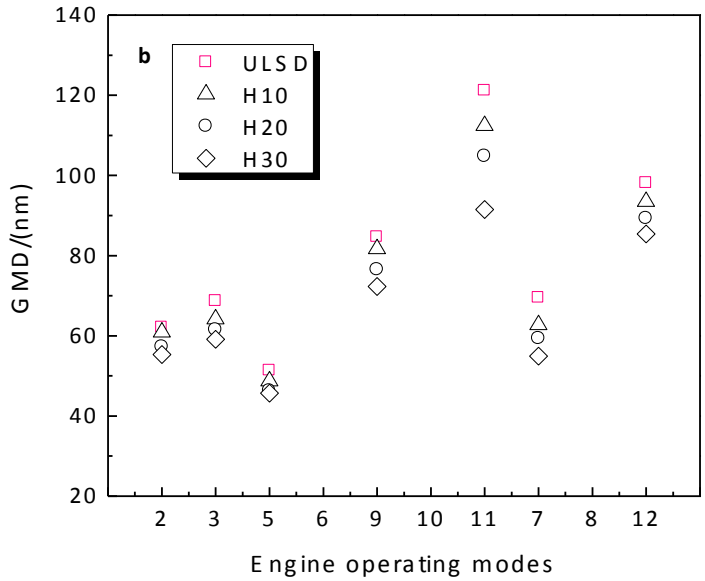


Engine combustion and emission with H_2 addition

Total number concentration

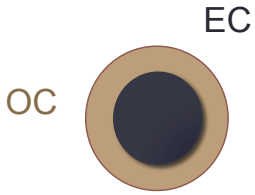


Geometry mean diameter



Physiochemical properties of DPM

- **Elemental/organic carbon content**

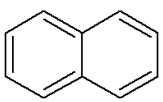


- EC: graphite, byproduct of incomplete combustion
- OC: complex mixture of unburned fuel, oil
- EC&OC are toxic, EC/OC fraction varies (load, fuel, engine et al.), PAHs in gas (OC) and particle phase (EC)

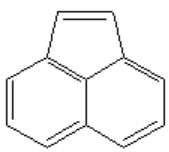
- **Focus**
- Same liquid fuel, Engine load and H2 input variation EC/OC content
- Same H_2 input, diesel and biodiesel and BD variation EC/OC content

Physiochemical properties of DPM

- Particle-phase PAHs
- ➢Engine: 2-aromatic rings (gas-phase), 3~4-semi-volitile phase, 4~6 –particle-phase PAHs



Nap



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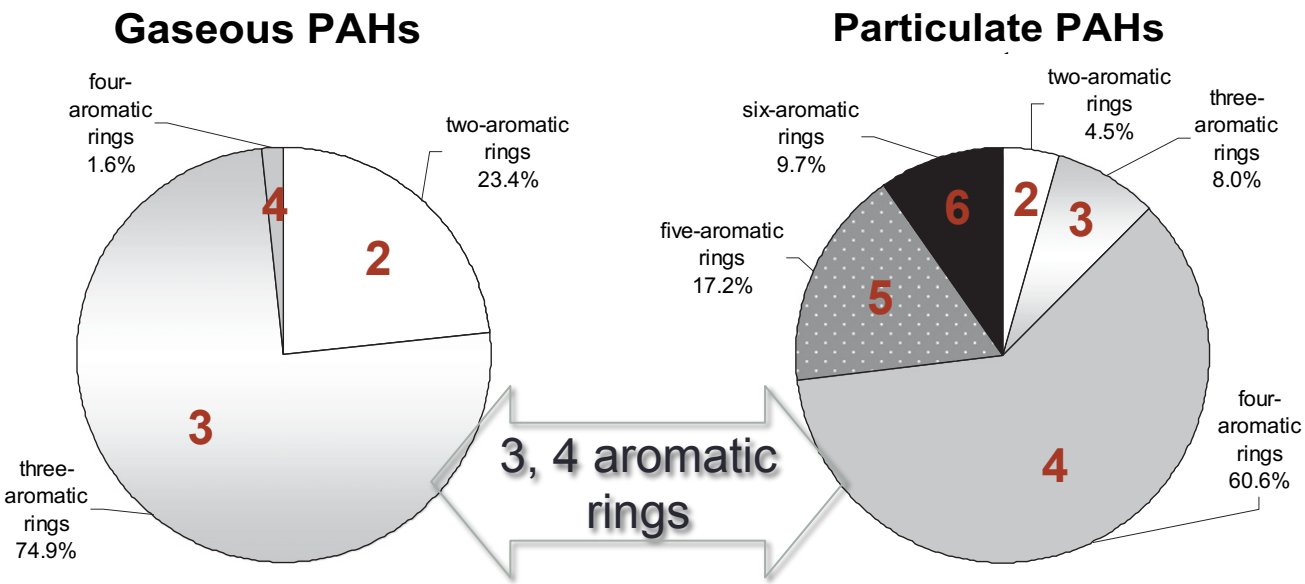
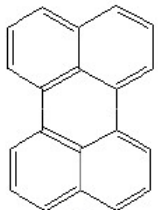




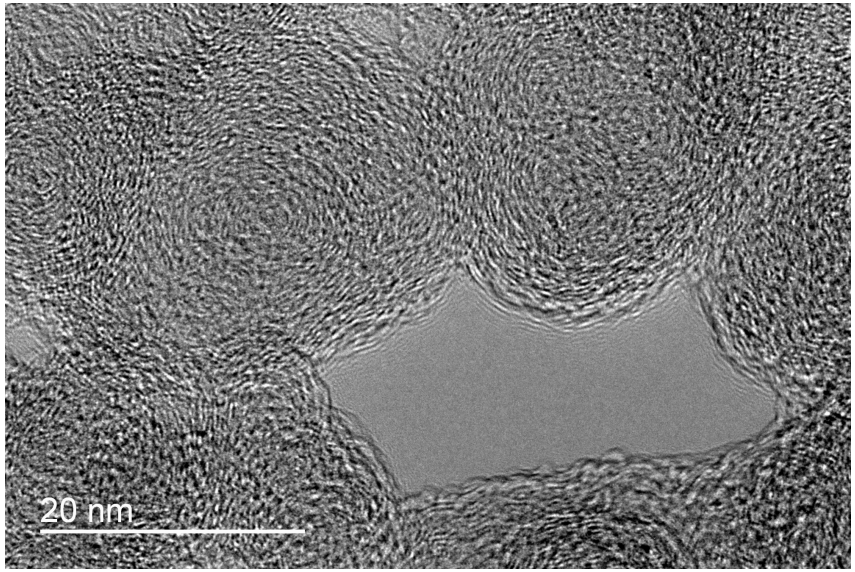
BghiP

USEPA 16 PAHs

Ho, et al. Atmospheric Environment. (2009).

Morphology of DPM

- Nano-HRTEM image processing



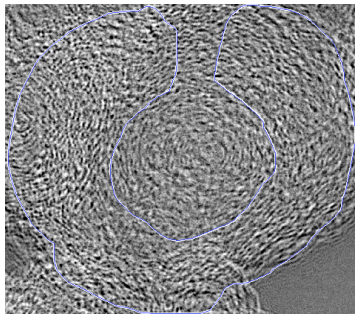
Morphology of DPM

- HRTEM image processing

1. Negative transformation
2. Selection of region of interest (ROI)
3. Contrast enhancement
4. Gaussian low pass filter
5. Top-hat transformation
6. Thresholding or binarization
7. Morphological opening and closing
8. Clearing fringes on the ROI border
9. Skeletonization
10. Removal of short fringe

Morphology of DPM

- HRTEM image processing



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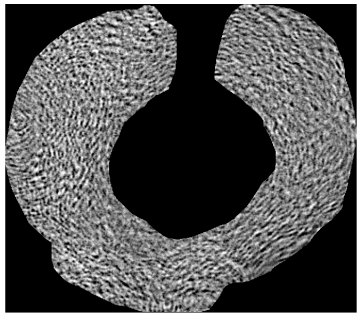

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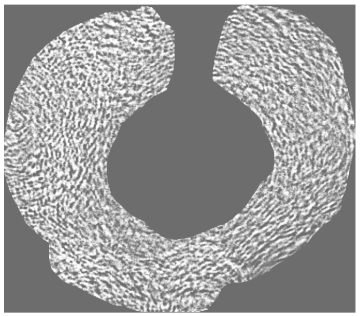

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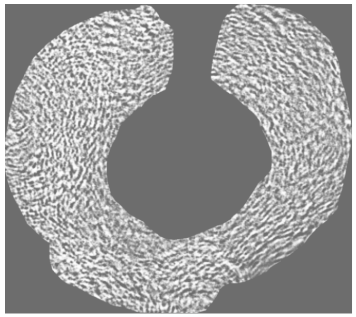

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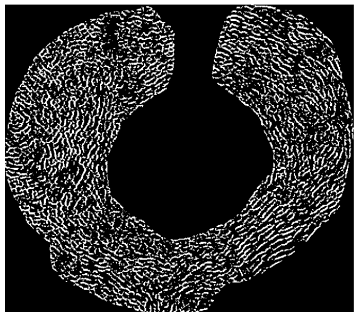

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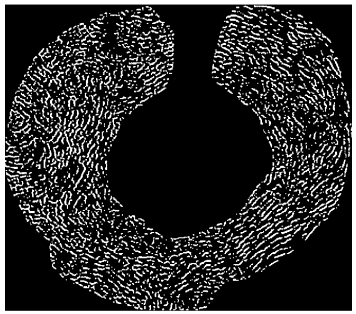

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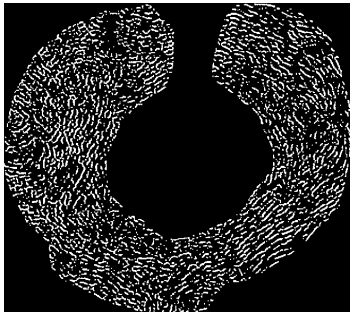

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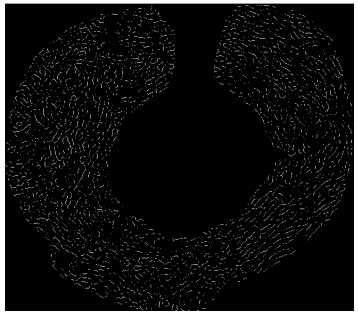

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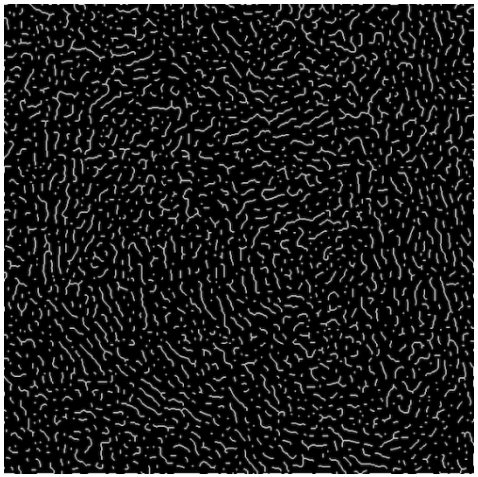
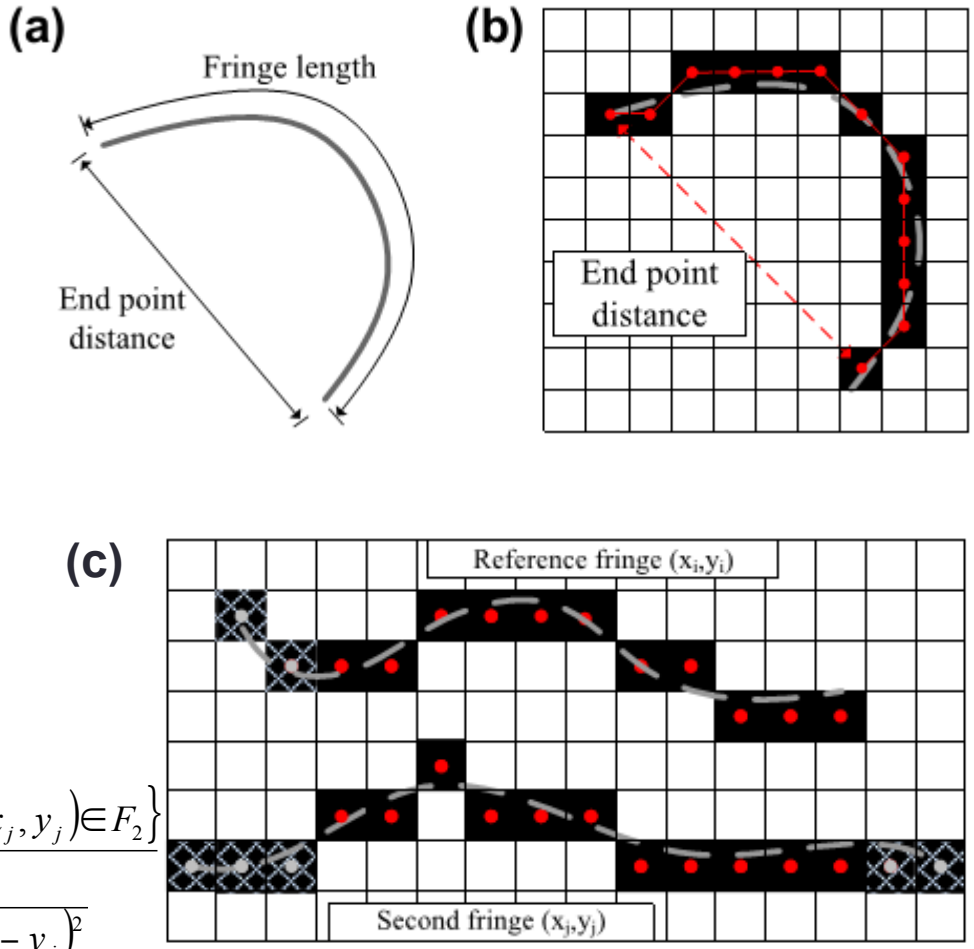
Morphology of DPM

- Lattice fringe characterization
  - (a) Fringe length
  - (b) Tortuosity
  - (c) Separation distance



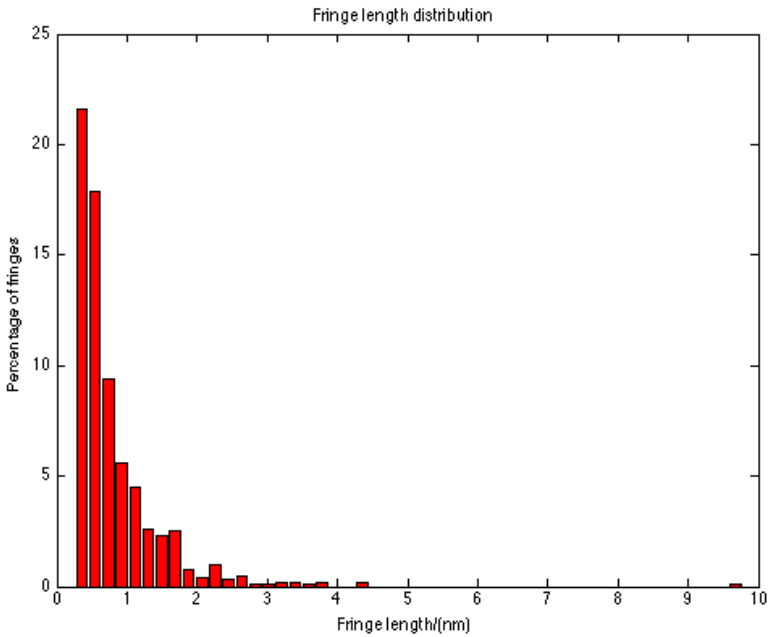


$$d_{ave} = \frac{\sum_{i=1}^{N} \min\left\{ d_{x_i y_i}(x_i, y_i), (x_j, y_j) \in F_2 \right\}}{N}$$

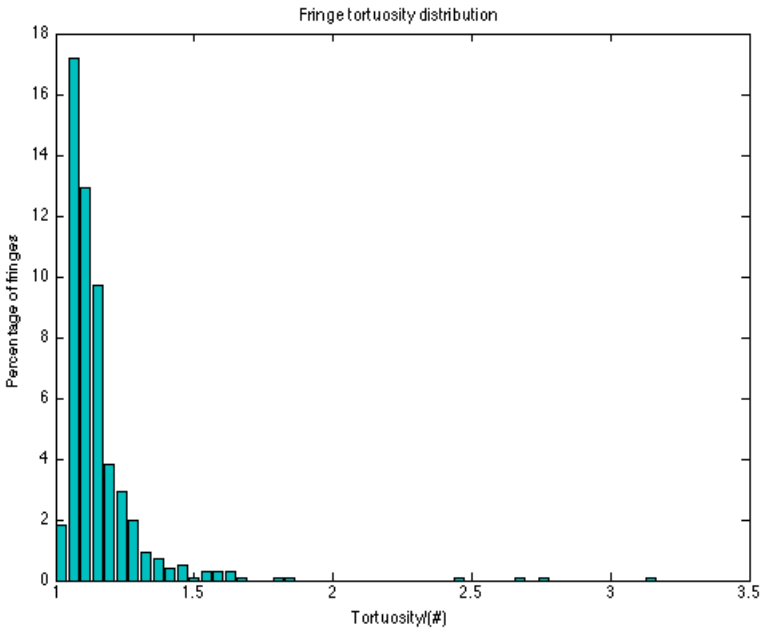
$$d_{x_i y_i}(x_i, y_i) = \sqrt{(x_i - y_j)^2 + (y_i - y_j)^2}$$

Morphology of DPM

Fringe length distribution



Fringe tortuosity distribution

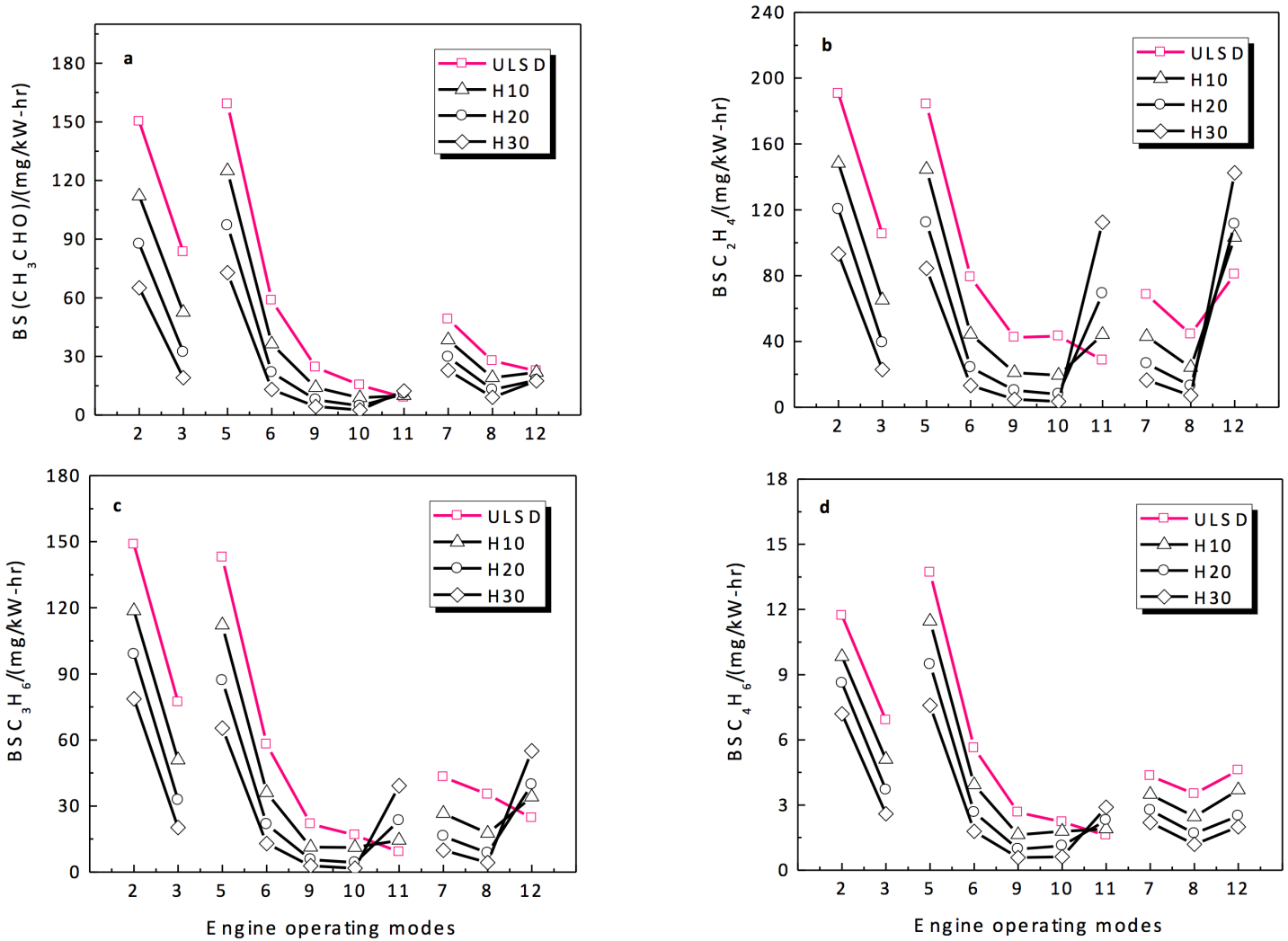


Unregulated emissions

- **Unregulated emission (extremely toxic)**
  Ion Molecule Reaction Gas Spectrometer
  - Formaldehyde (HCHO), acetaldehyde (CH_3-CHO)
  - Ethene (C_2H_4), ethyne (C_2H_2), 1,3-butadiene (C=C-C=C)
  - Benzene, toluene, xylene (BTX)

- **Focus**
  - Same liquid fuel, Engine load and H_2 input variation
  - Same H_2 input, diesel and biodiesel and BD variation
  - Variation of unregulated emissions

Unregulated emissions



Thanks!