A Planar Mixing Layer Flame (PMLF) configuration to perform spatially resolved High-Resolution Differential Mobility Analysis (HR-DMA) in diffusion flames

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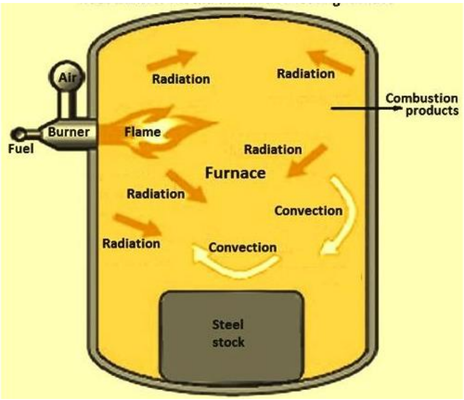
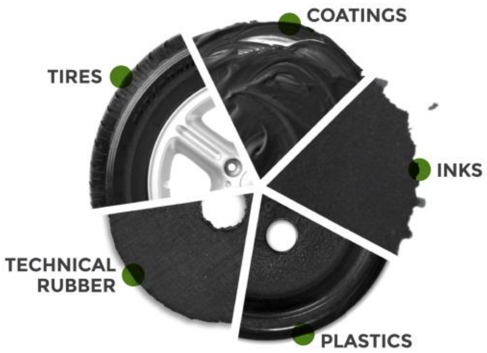
Motivation

Soot emissions from combustion sources pose significant hazards to human health and the environment and are a substantial contributor to climate change

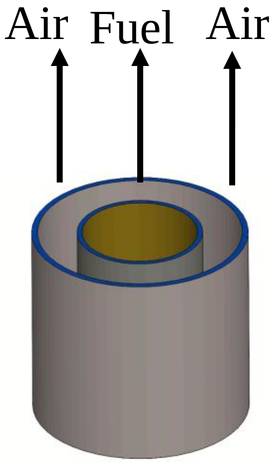




- <u>It is important to understand soot nucleation in flames</u>

Diffusion flames' canonical configurations

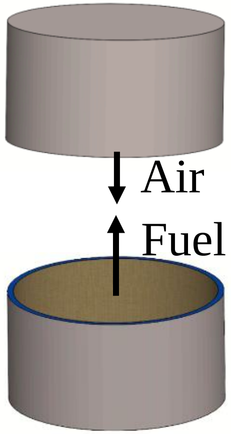
Co-flow diffusion Flame

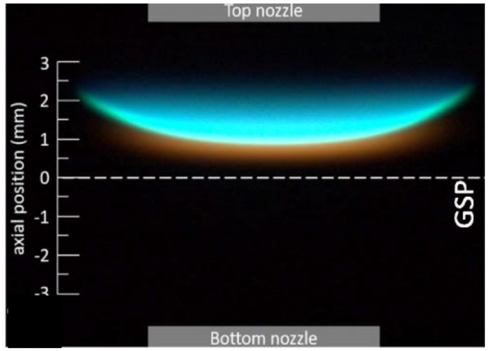


- Can't decouple pyrolysis from oxidation
- Axial symmetry prevents the sampling of products with spatial resolution
- Buoyancy affects the temperature time history in a complicated manner

Santoro et al, CNF, 1981

Counterflow diffusion Flame (CF)

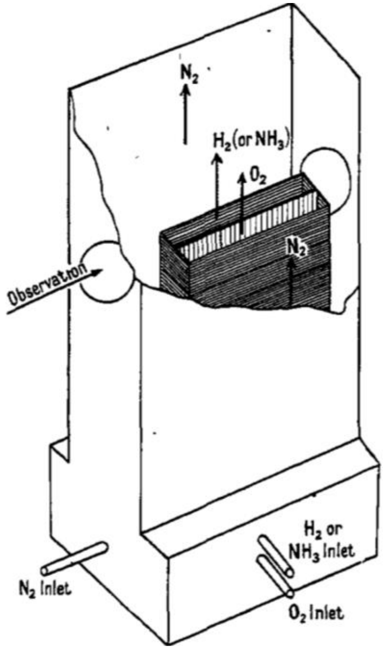


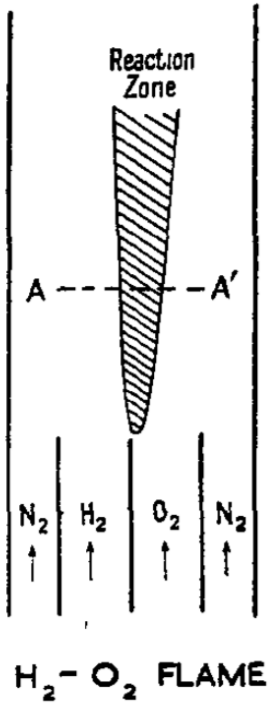


- 1D easy to model structure
- Buoyant instabilities at low strain rates
- Experimental limitation on flame thickness
- Inaccessibility to intrusive dilution probes

Pandya and Weinberg, Proc. R. Soc. A, 1964

Wolfhard and Parker Flame

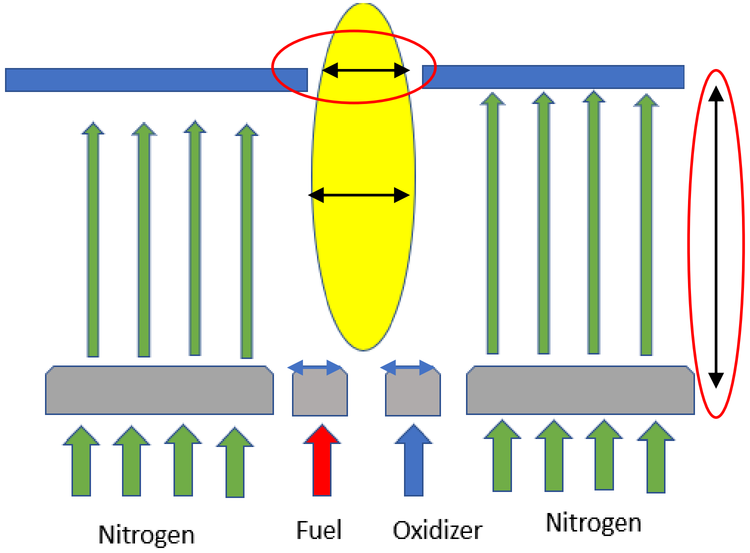




- Enclosure is essential for stability
- Not suitable for sampling techniques
- Can be stabilized only at low HAB

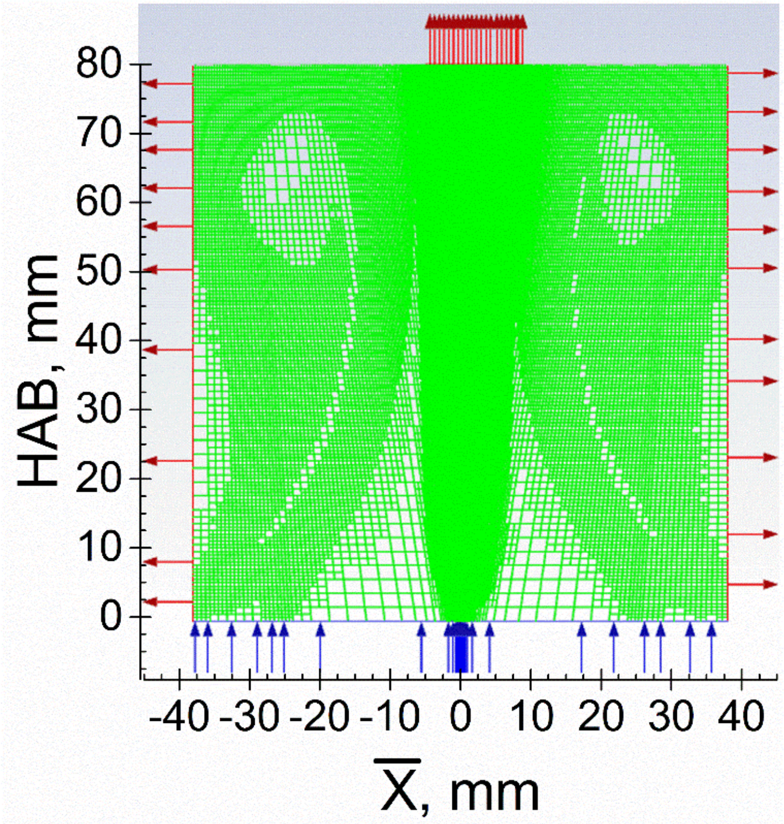
Wolfhard and Parker, PPS 1949

PMLF idea and 2D-CFD model



- Slit width and horizontal position
  - Maximum stability
  - Minimum interaction with the plate
- Nozzle size
  - Prevent dilution by nitrogen shielding
- Vertical position of the plate
  - The thickest flame with best stability

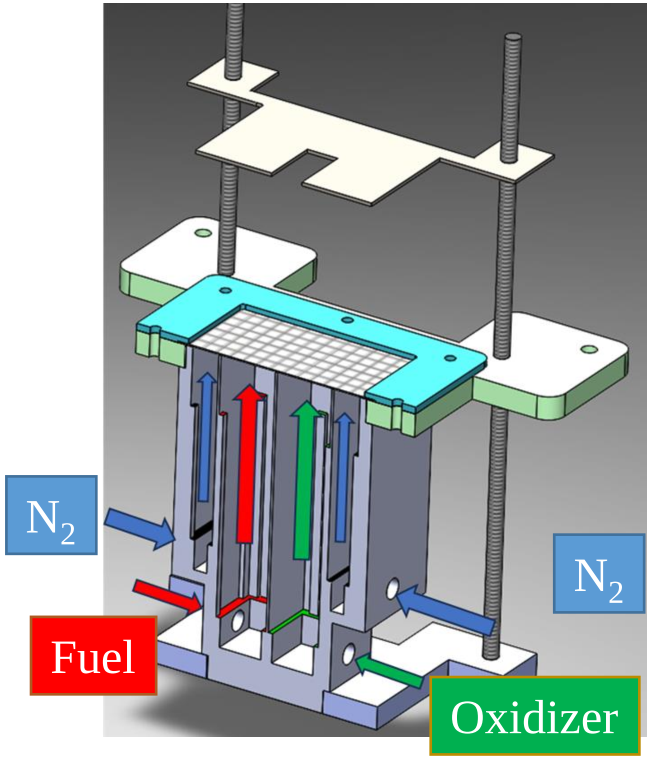
- Plug flow inlet (0.2 m/s)
- Pressure outlet (Bernoulli approximation)
- Adiabatic wall boundary for the plate



- Adaptive mesh refinement is utilized
- Mesh independence is achieved for limit of variation within the cell of the values (G=1%) and their gradient (C=2%)
- USC and ABF chemical kinetic models are used

Appel et al., Combust. Flame, 2000 . *Wang, et al. "USC Mech Version II, 2007.*

Burner design and PMLF structure



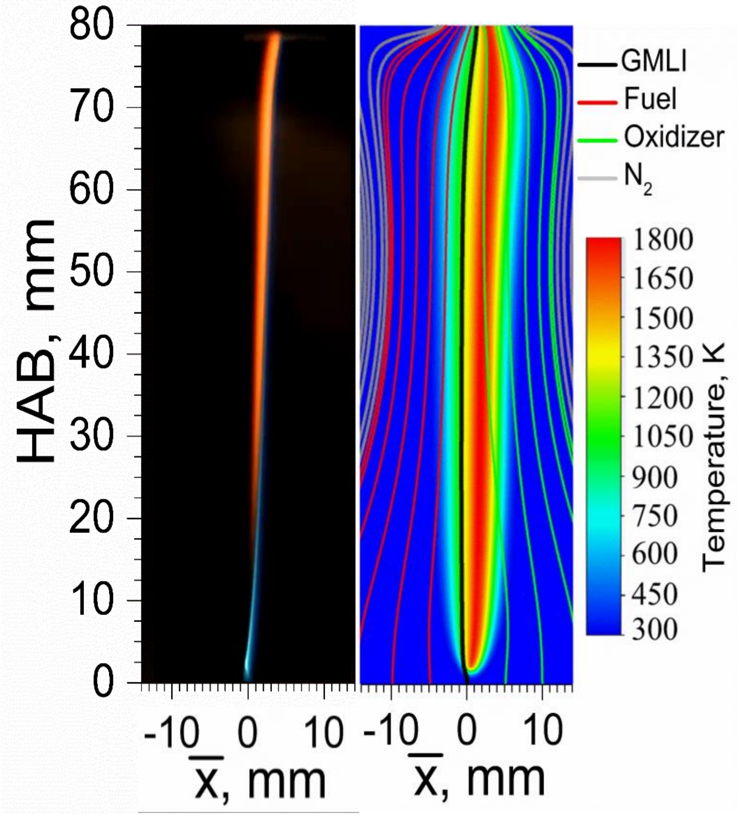
0.250 C_2H_4+ 0.750 N_2

0.172 O_2+ 0.828 N_2

Z_{st}= 0.183

Carbone et al. Combust. Flame, 2015.

- T_{max} is in the oxidizer stream
- Strain rate decreases as the Hight Above the Burner (HAB) increases
- Thickness at HAB=50 mm ($\approx 12mm$) is 3 times thicker than counterflow flames investigated in the literature
- Flame does not flicker (the standard deviation of displacement is less than 0.3mm even when a dilution sampling probe is being used)



The Gas Mixing Layer Interface (GMLI) is the surface composed of all streamlines separating the Fuel from the Oxidizer jets

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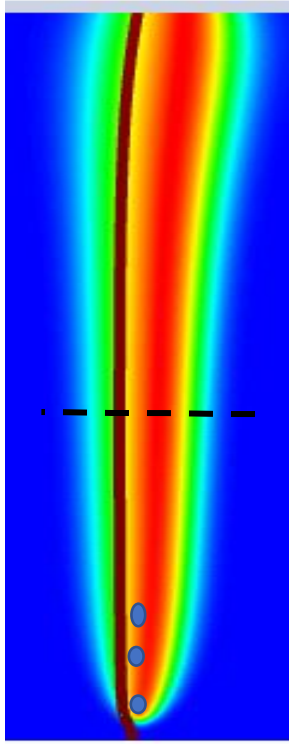
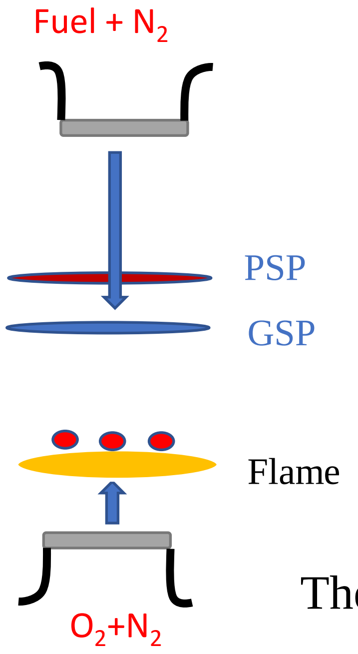
Self-similarity of PML and CF

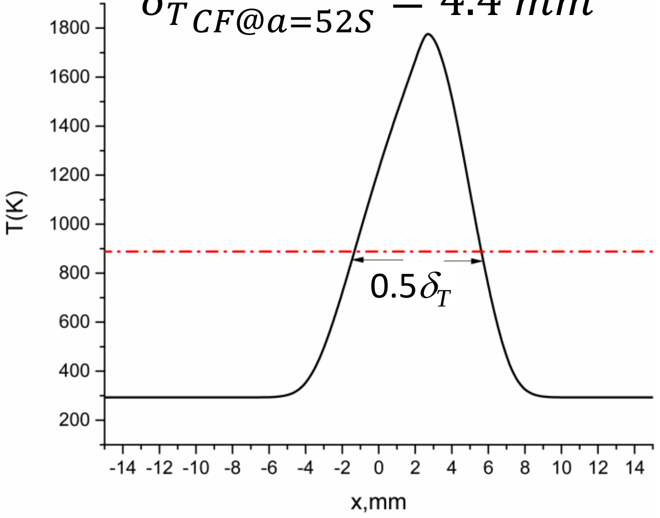
- *Capillary sampling followed by GC/MS analyses*



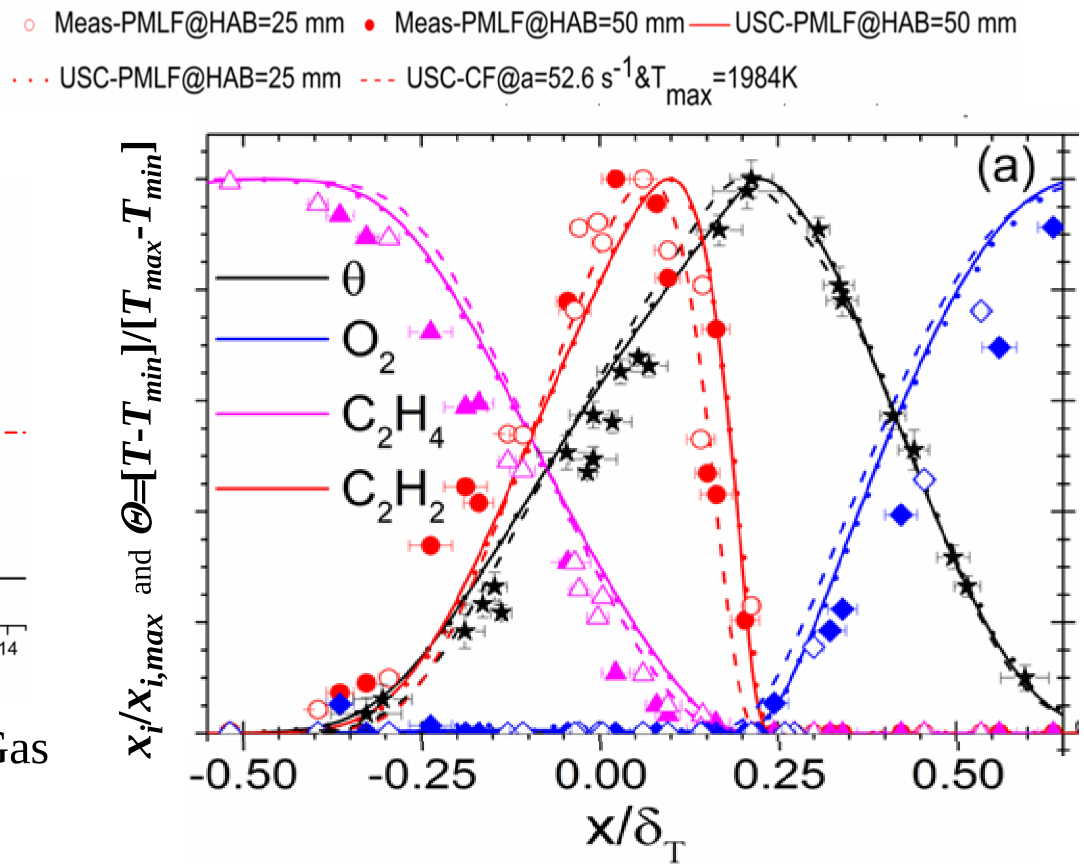
PMLI-GMLI



$$\delta_{T\,PML@HAB50} = 12mm$$
$$\delta_{T\,CF@a=52S} = 4.4\ mm$$



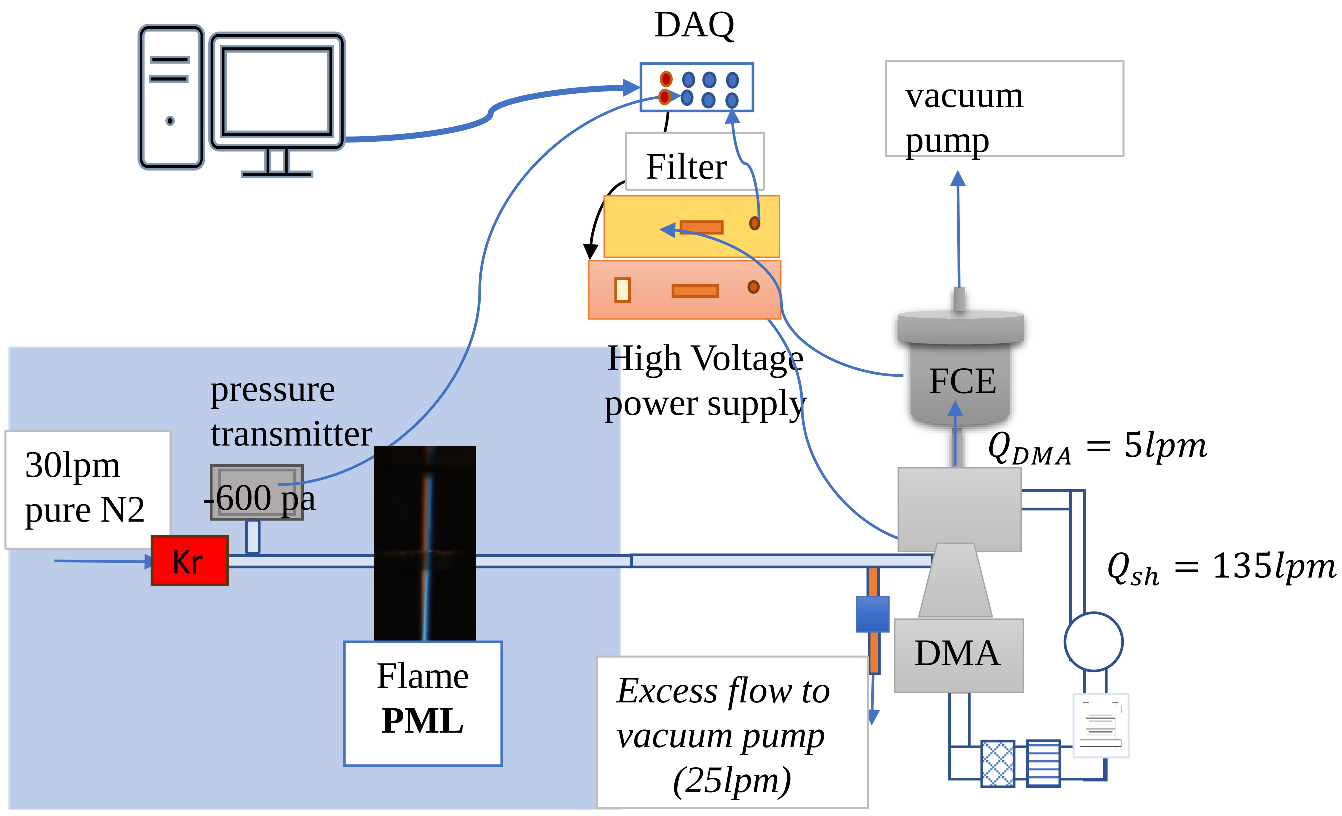
The GMLI is the equivalent to the Gas Stagnation Plane (GSP) in CF



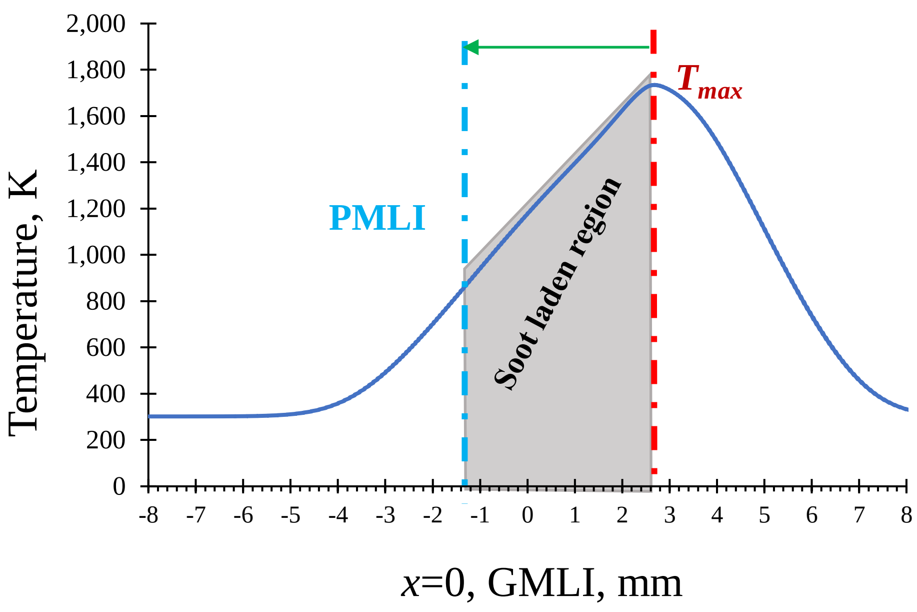
The Particle Mixing Layer Interface (PMLI) differ from the GMLI because of the thermophoretic velocity $\left(v_{th} = -0.554v\frac{\nabla T}{T}\right)$, similar to the Particles Stagnation Plane in CF

- A diffusion self-similarity exists between the horizontal cross-sections of the PML and CF at the same stoichiometric mixture fraction
- The flame maintains stability when examined using capillary sampling or thermocouple

HR-DMA Measurements' Setup



$D_{orifice}$ µm	Nominal Dilution ratio, DR	Residence time, ms
150	≈2000	$\Delta t \approx 60\ ms$
100	≈4400	
80	≈6900	



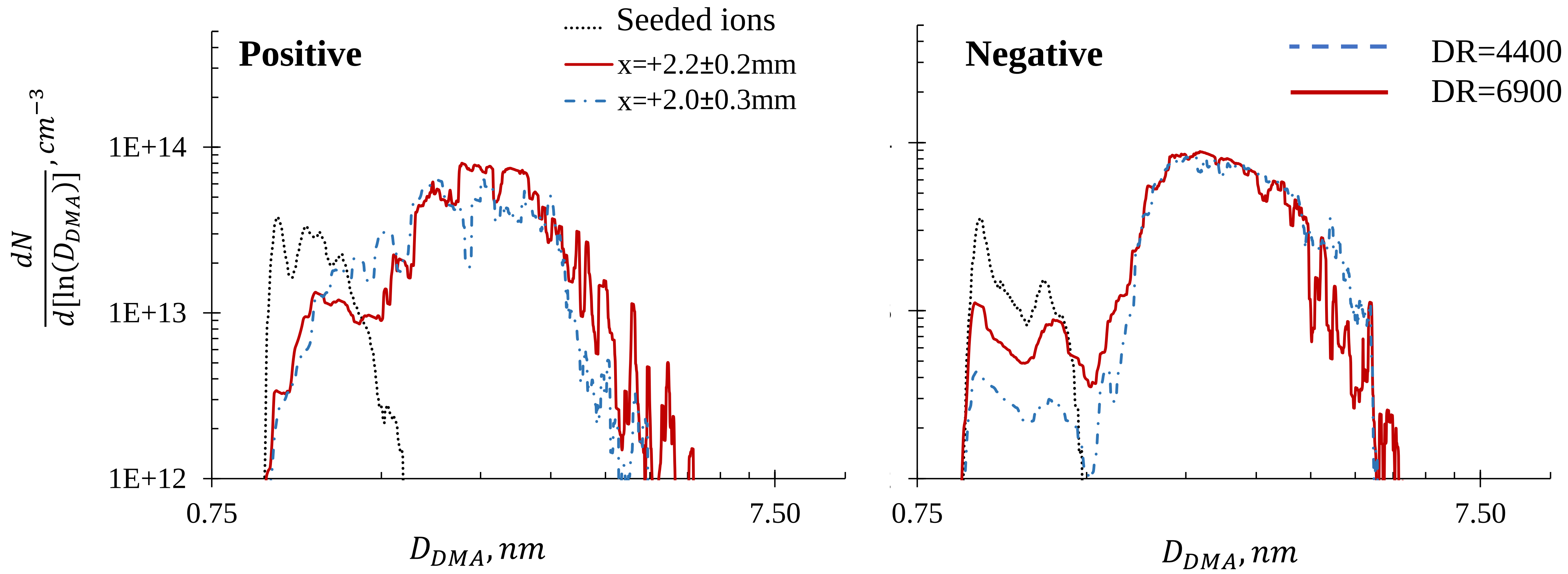
$$\frac{dn}{d[ln(D_{DMA})]} = n_{FC}(D_{DMA}) \cdot \frac{2 \cdot Q_{sh}}{Q_{DMA}} \cdot \frac{1}{P_{prob}(D_{DMA})} \cdot \mathrm{DR} \cdot \frac{T_{in-DMA}}{T_{flame}} \cdot \frac{1}{\eta_{charge}}$$

Kumar et al., Atmosph. Env. , 2008

Carbone et al., AST, 2016

Effect of DR

HAB=50mm

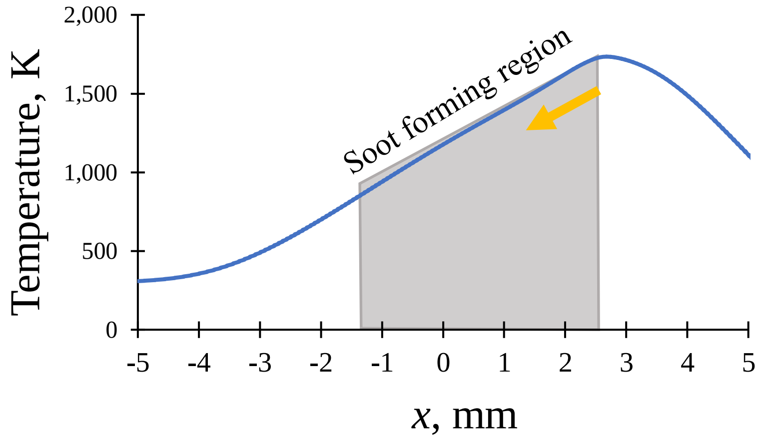


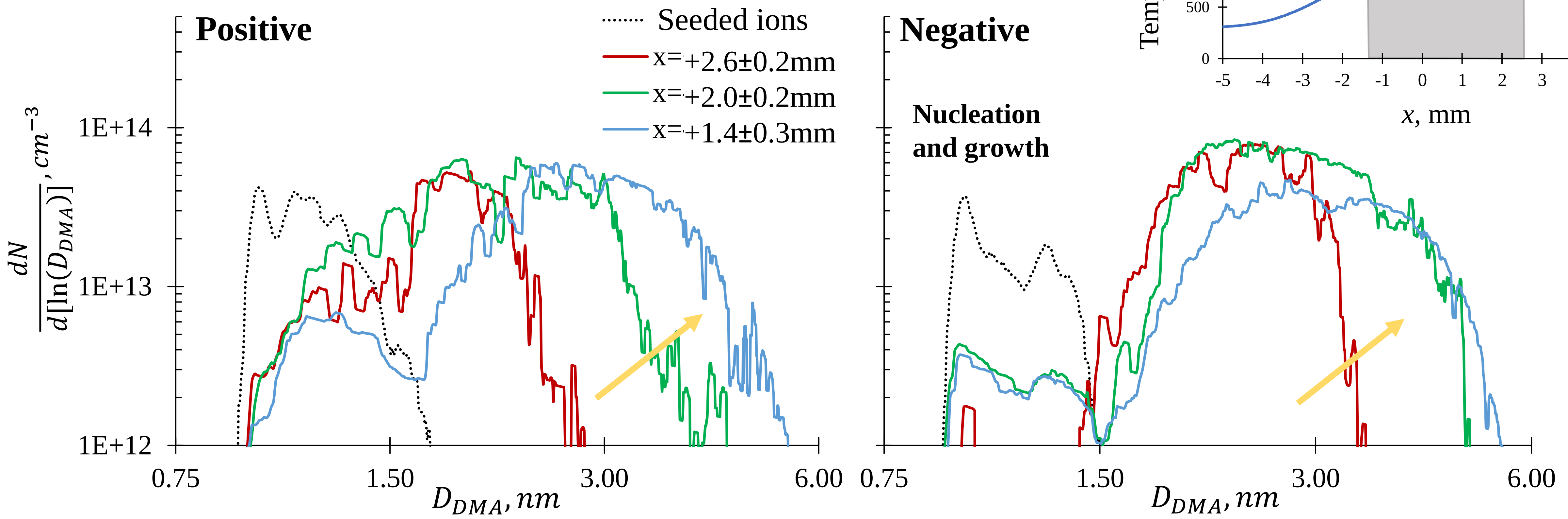
- The measured Size Distribution Function (SDF) is approximately independent of dilution ratio at all HABs

Size Distribution, Phase 1

HAB=50mm

Orifice size: 100µm (DR=4400)





- Soot nucleation occurs in the proximity of the maximum temperature and is followed by growth

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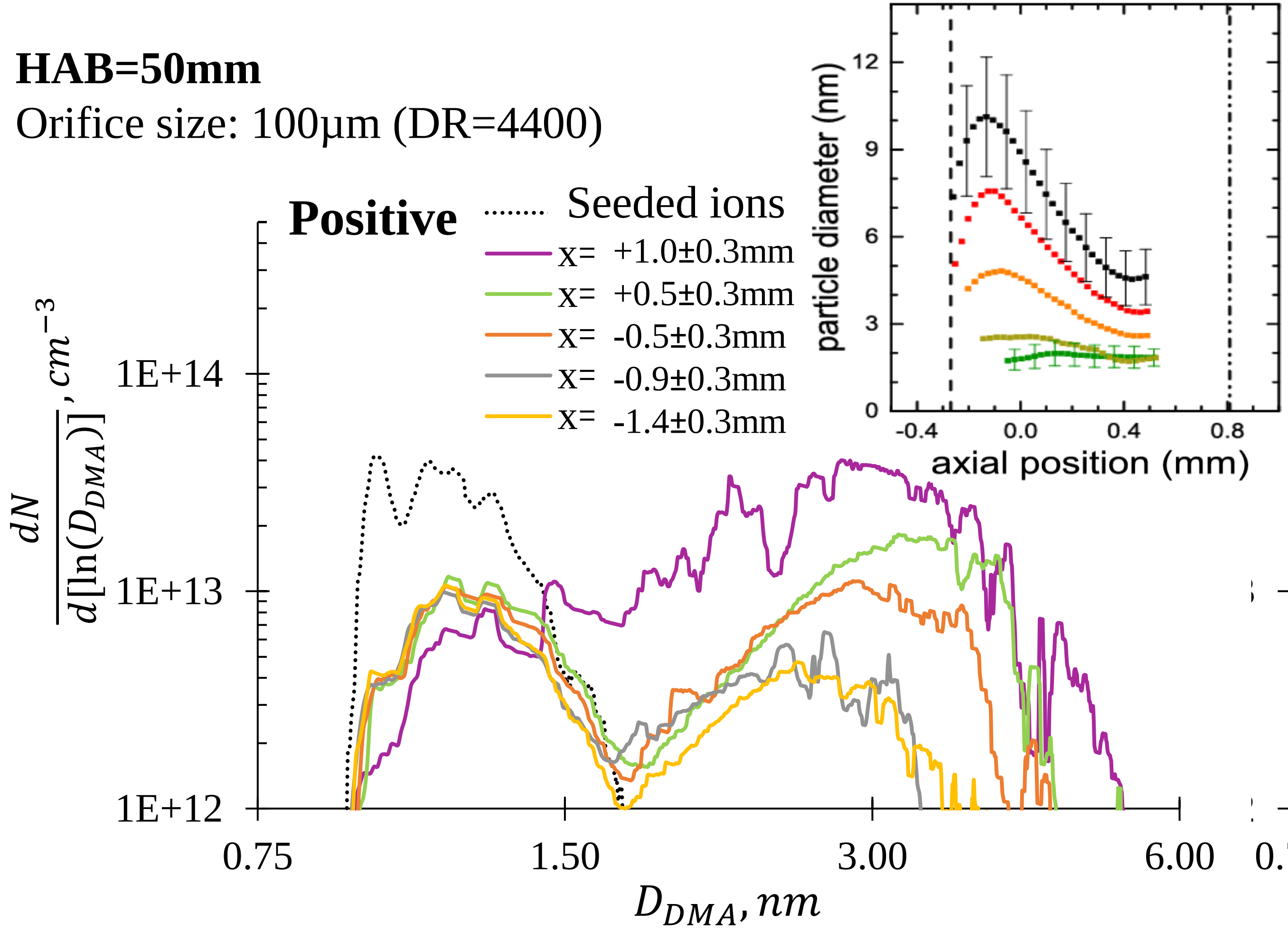
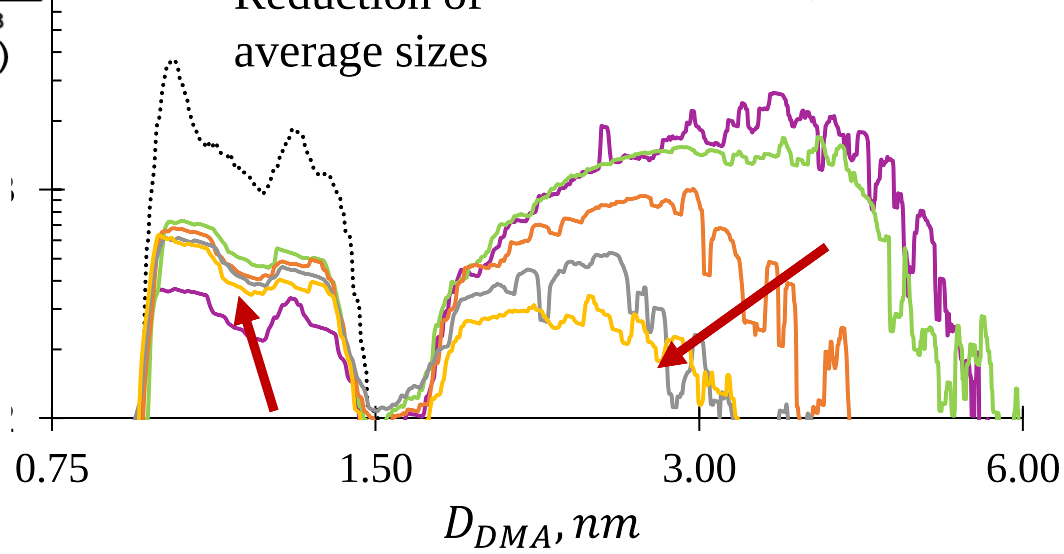
Size Distribution, Phase 2

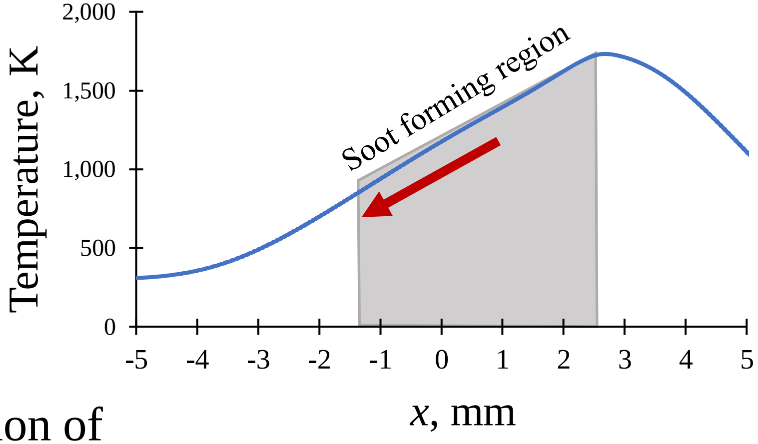
UCONN

HAB=50mm

Orifice size: 100µm (DR=4400)





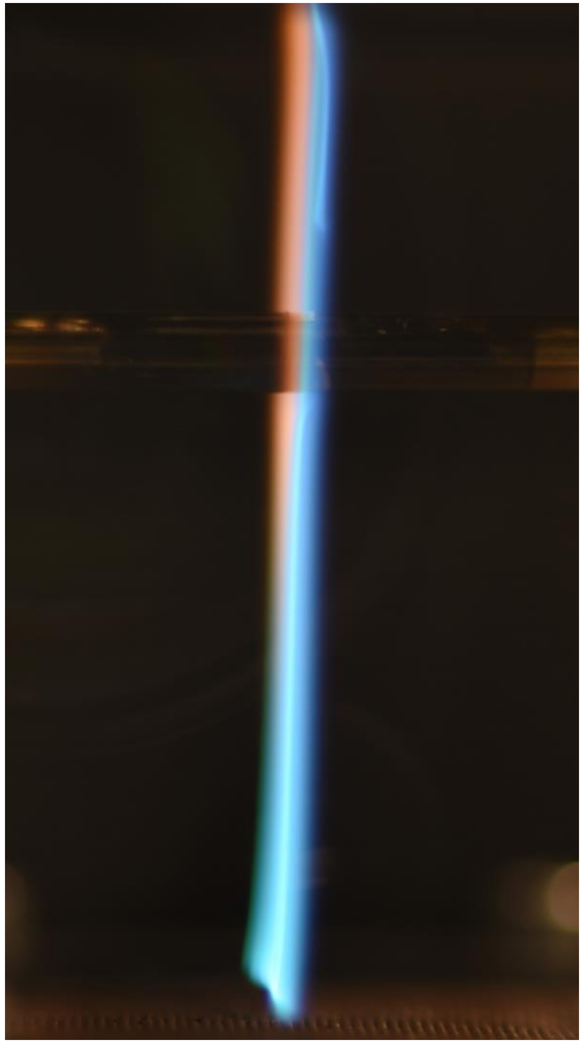


- Cooling the flame products can result in secondary particle nucleation at temperatures below 1400K

Gleason et al, 2021

Carbone et al, 2023

Conclusion



- The horizontal thickness of the Planar Mixing Layer Flame (PMLF) increases at increasing Heights Above the Burner (HAB)
- The PMLF remains very stable while its sampling is performed with an intrusive horizontal tube dilution probe (as well as during capillary sampling, or fine thermocouple measurements).
- The PMLF has a boundary layer diffusion self similar structure equivalent to that of a one-dimensional Counterflow Flame (CF) with the same stochiometric mixture fraction, but it can be is at least 3 times thicker compare to CF experiments.
- Dilution sampling followed by HR-DMA quantifies the Size Distribution Function (SDF) of soot nucleating in the proximity of the hottest PMLF oxidation layer.
- Nucleation is followed by growth as soot is advected away from the PMLF oxidation layer.
- The SDF re-shift toward smaller size as the local temperature drops below 1450K so that HR-DMA confirm a low temperature nucleation.

Thank you For your attention

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