Consiglio Nazionale delle Ricerche

Istituto per l'Energetica e le Interfasi – Milano ***ITALY***

Investigation by optical techniques of the effect of hydrogen addition in rich premixed ethylene-air flames

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Aim of the work

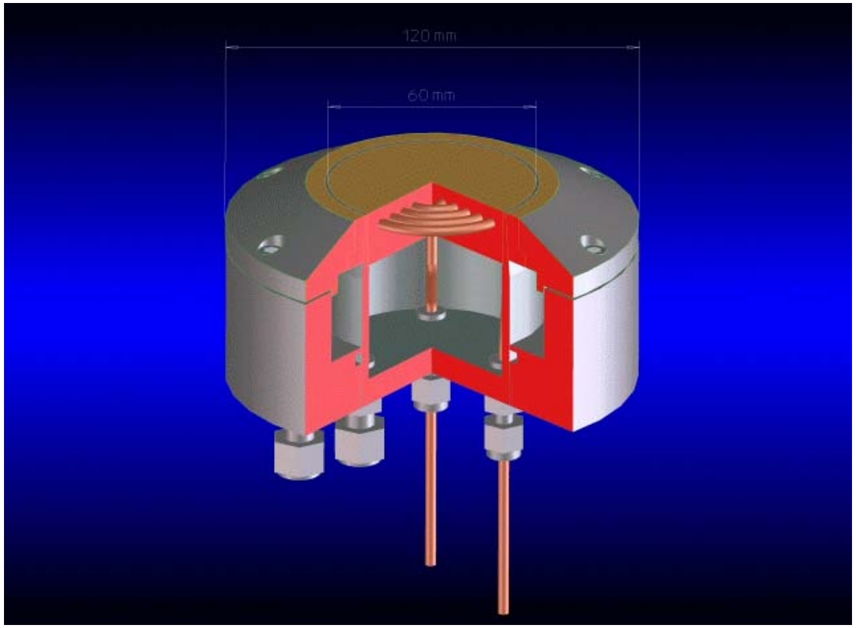
effects of hydrogen addition on:

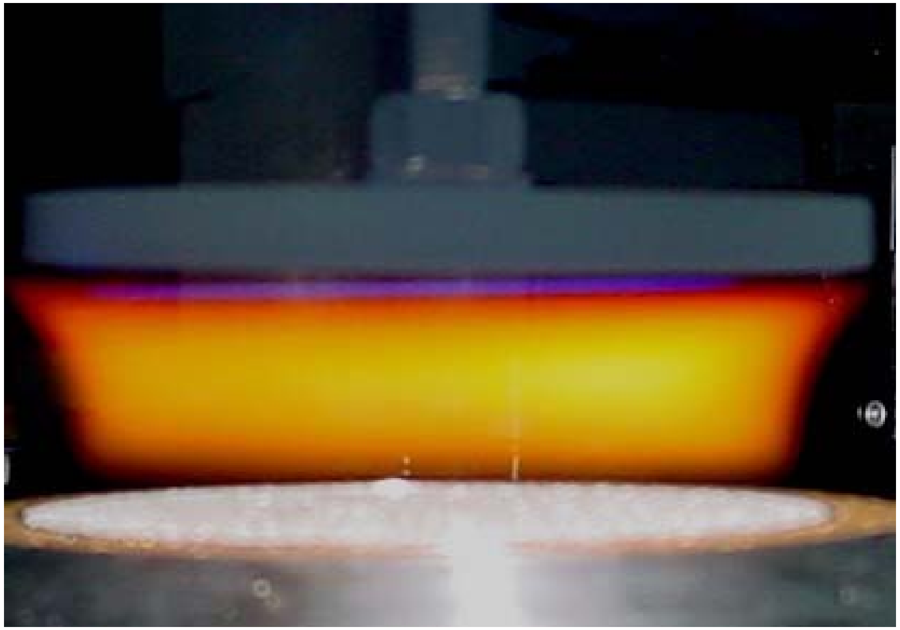
- ✓**Flame Structure**
- ✓**Gas Temperature**
- ✓**Soot content**

Laminar premixed flat flames

McKenna burner

- Bronze porous plug : ϕ = 60 mm
- Co-annular porous bronze ring : s = 6 mm
- Stabilization plate: ϕ = 60 mm, HAB = 20 mm





Flame conditions

- ✓ total flow rate = 10 l/min
- ✓ cold gas flow velocities = 5.84 cm/s
- ✓ C/O ratio = 0.775

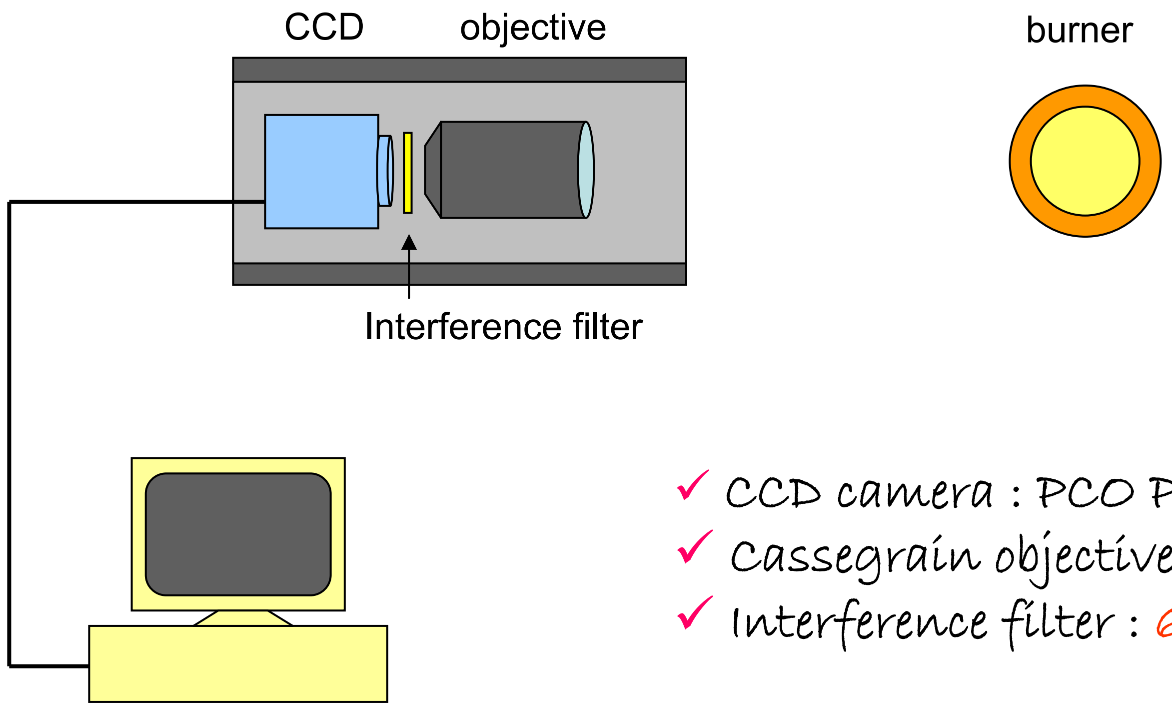
constant !!!

$\phi = 2.34$

flame	C_2H_4 [l/min]	H_2 [l/min]	H_2/C_2H_4*100	Air [l/min]	Φ global
A	1.400	0	0	8.60	2.34
B	1.380	0.138	10	8.46	2.425
C	1.360	0.272	20	8.34	2.528
D	1.346	0.404	30	8.25	2.639
E	1.328	0.531	40	8.14	2.761
F	1.310	0.655	50	8.03	2.895

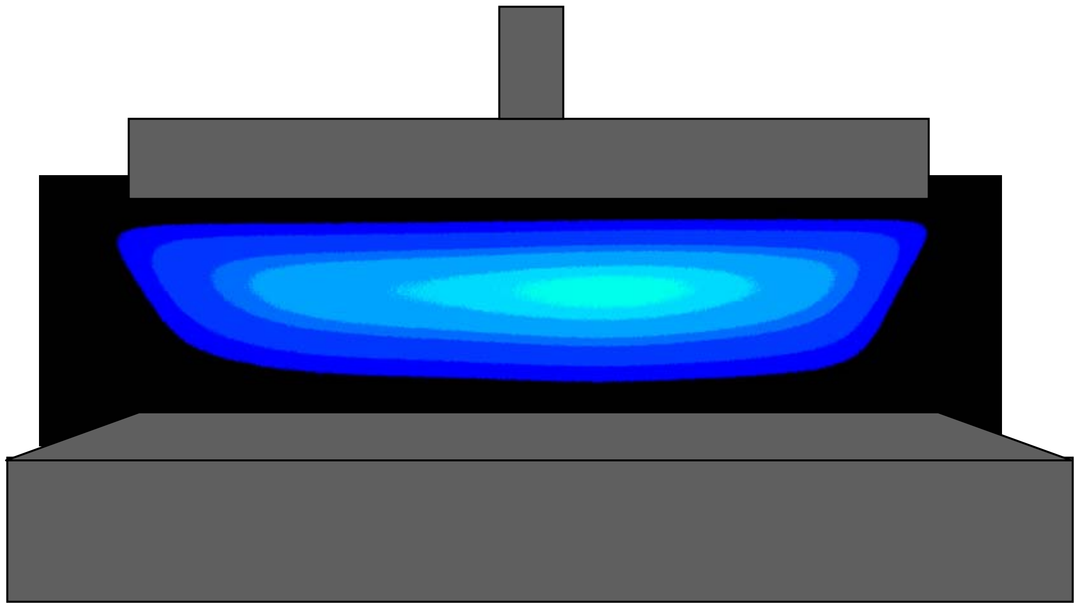
1. Flames Structure

Flames light emission measurements



- ✓ CCD camera : PCO Pixelfly, 12 bit
- ✓ Cassegrain objective : Nikon, 500 mm
- ✓ Interference filter : 647 nm, $\Delta\lambda = 10$ nm

Typical images of the flame emission



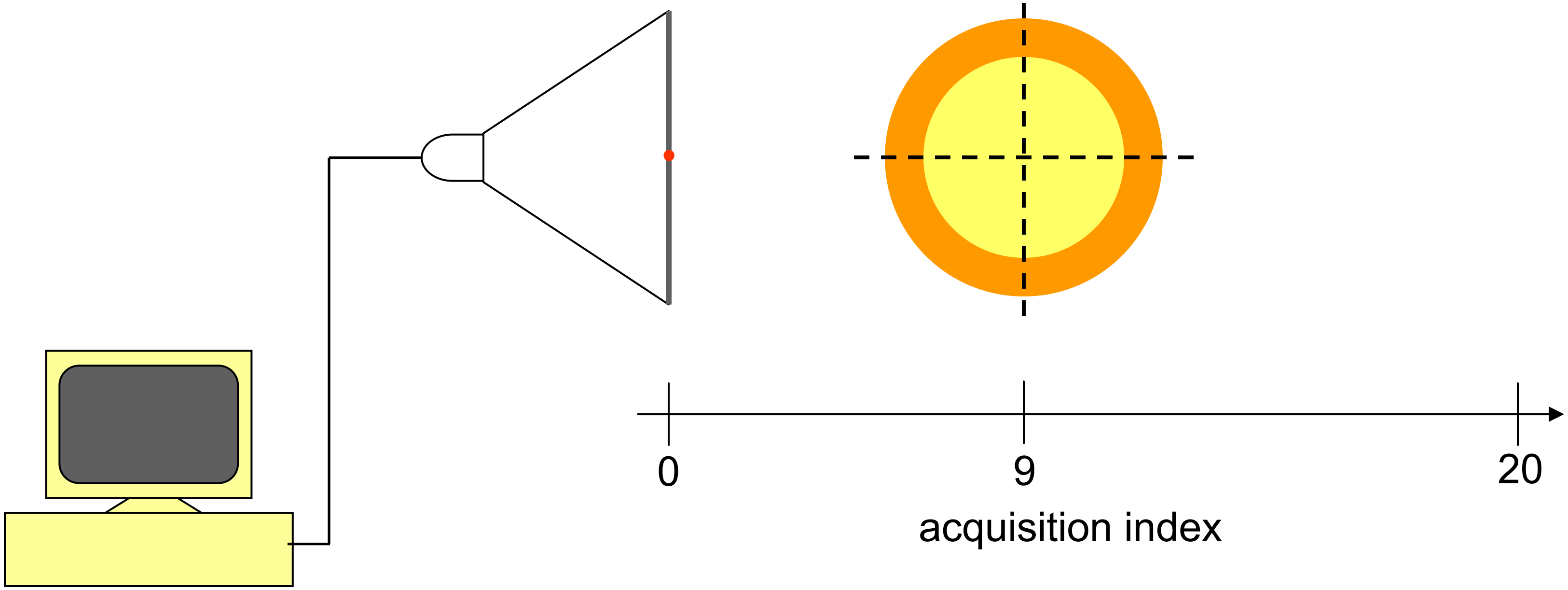
- ✓ quite uniform distribution of flames emission
- ✓ decrease of the emission intensity increasing the hydrogen content.

2. Gas Temperature

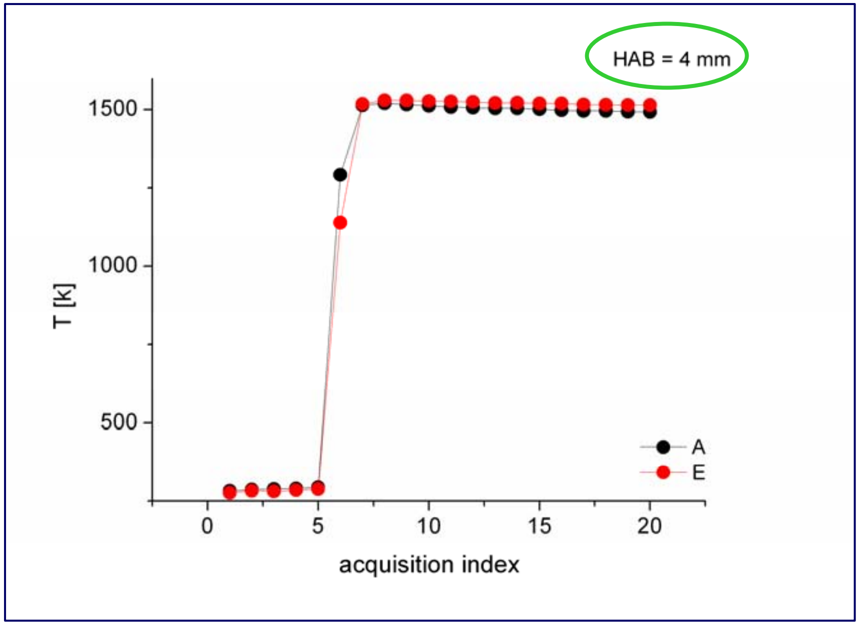
Thermocouple measurements

Pt/Pt-Rh(10%) : d = 127 μm, uncoated (fork)

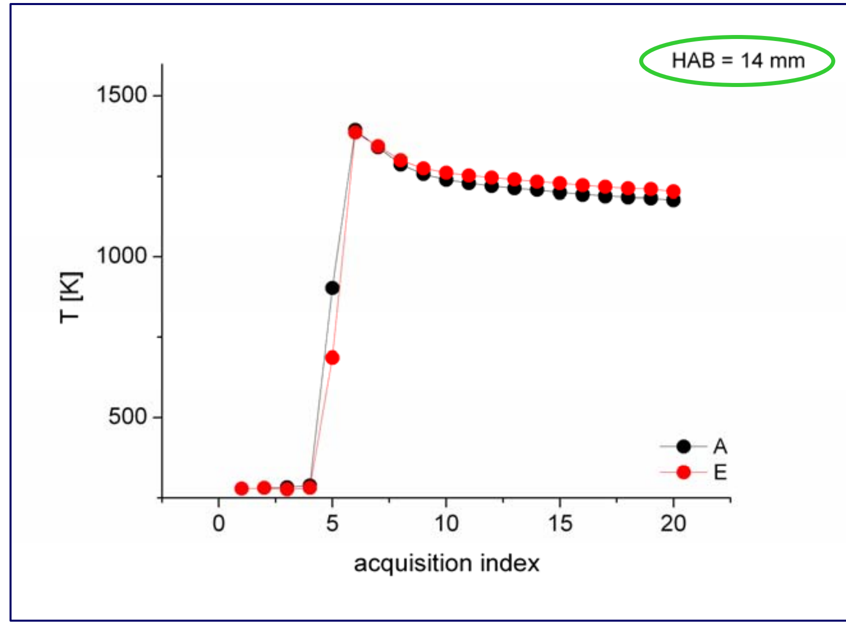
Pt/Pt-Rh(10%) : d = 50 μm, uncoated (in alumina tubing)



Temperature history of the junction (uncorrected, row data)



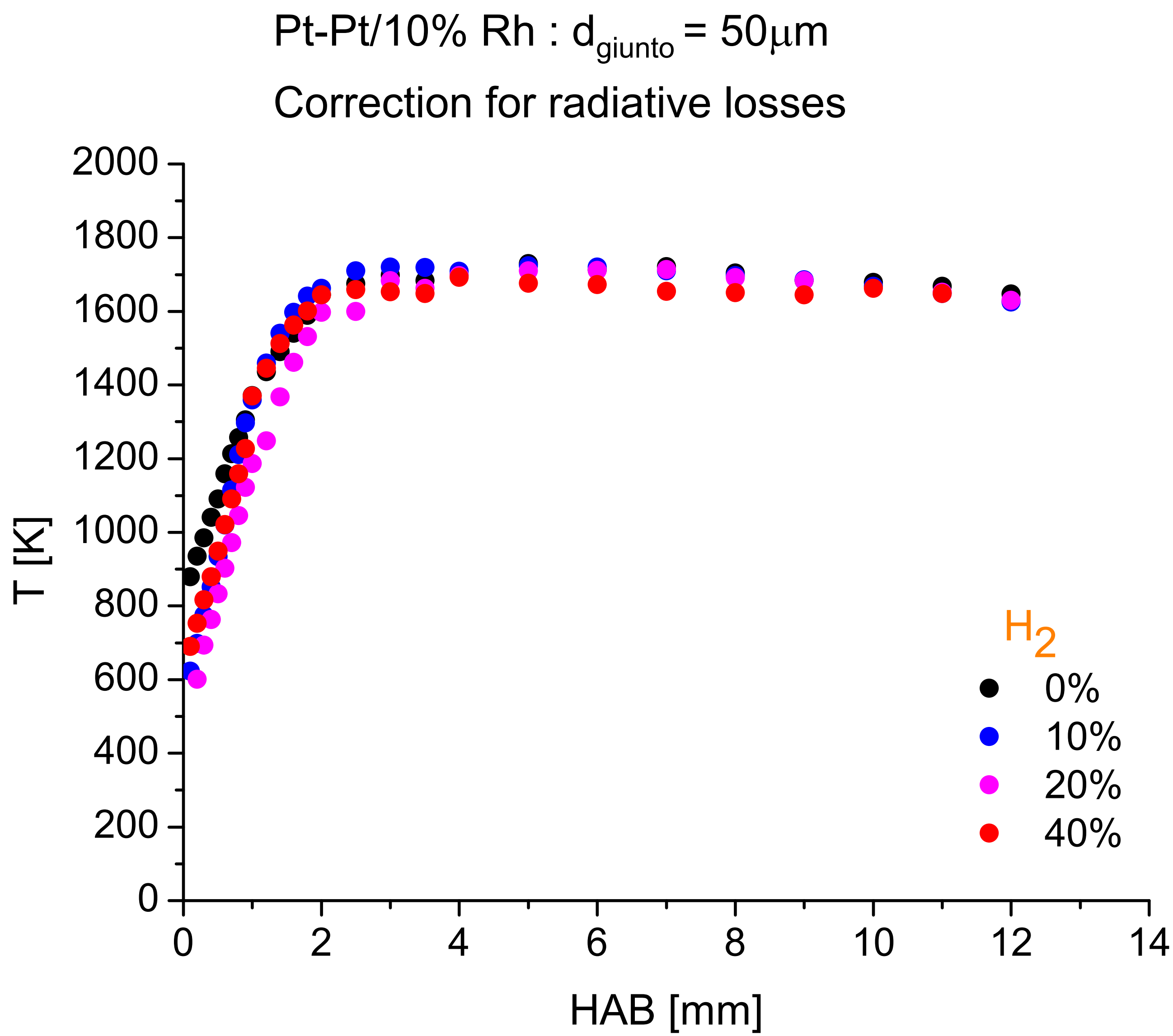
"clean zone"



"sooting zone"

The temperature decrease continuously as soot deposits on the junction

Temperature axial profiles



Emission technique

detection efficiency coefficient can be determined with a calibrated lamp

- ✓ Radiation emission from soot

$$I_s = \varepsilon_s(\lambda, fv) I_{BB}(\lambda, T_s) \tau_{s\lambda}$$

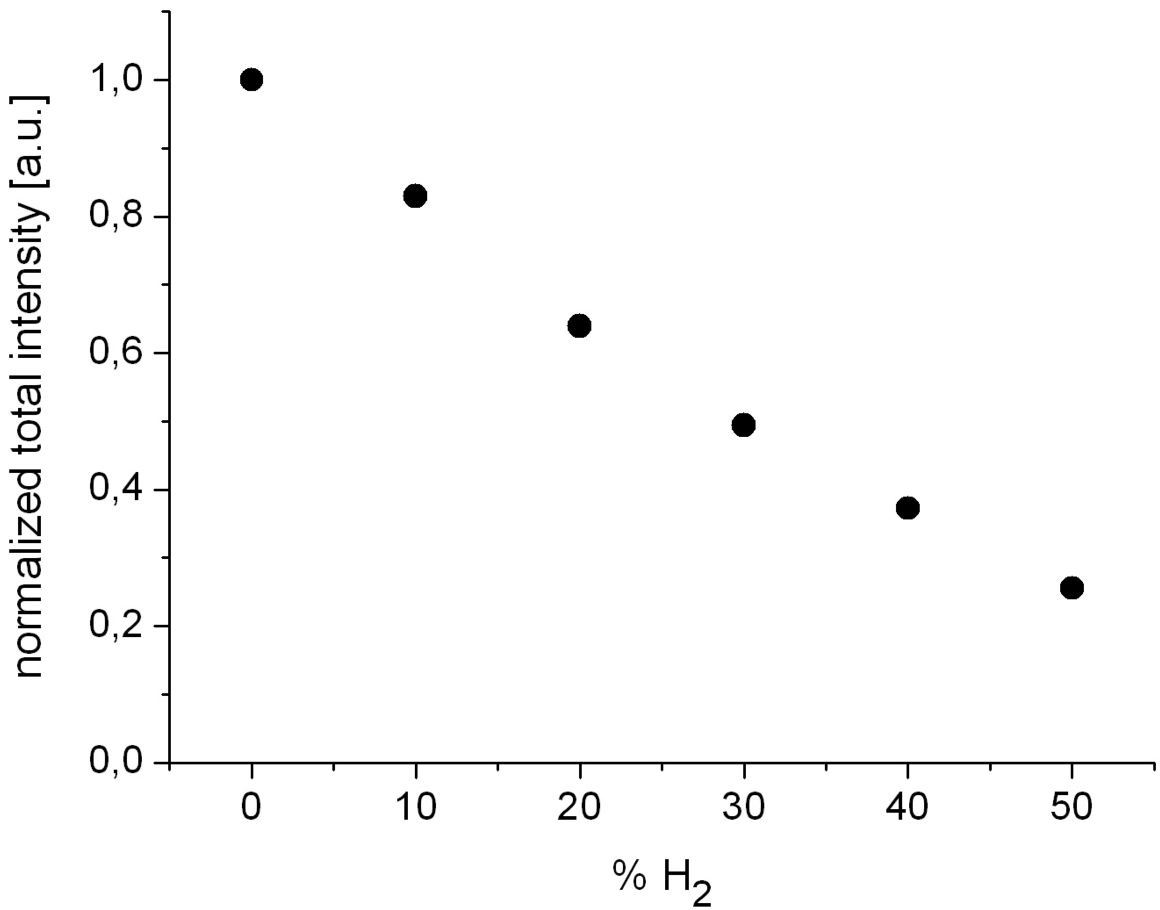
$$\varepsilon_s(\lambda, f_v) = 1 - \exp(-K_{abs} L)$$

$$K_{abs} = \frac{f_v 6\pi E(m)}{\lambda} = f_v\, l_{abs}$$

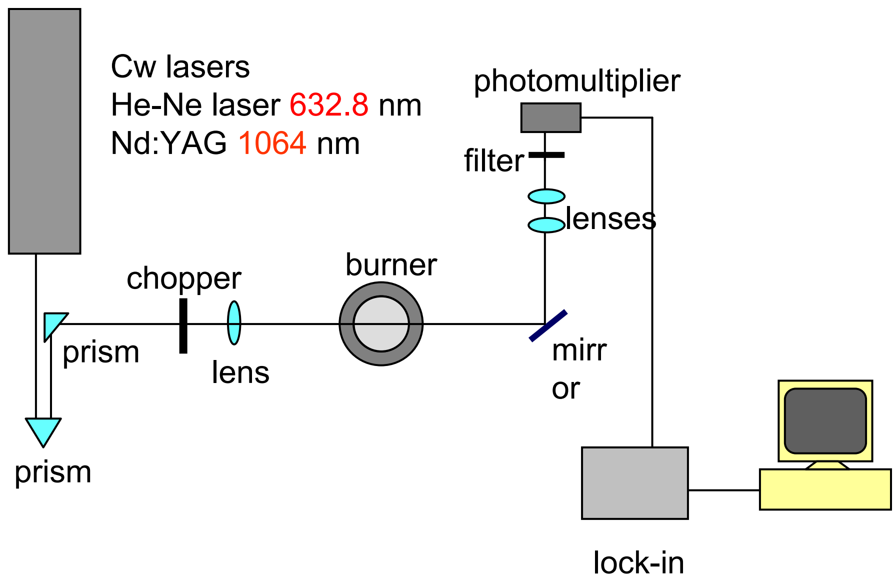
If $T_{s\,without\,H2} \approx T_{s\,with\,H2}$ ⇒ $I_s \div f_v$

$\int_V I_s \approx \int_V f_v$ = total amount of soot

Soot reduction by hydrogen addition



Laser Extinction



$$\tau_\lambda = \ln\left(\frac{I_L}{I_0}\right) = -K_{ext}L$$

$$f_v = \frac{\lambda K_{ext}}{6\pi E(m)}$$

dep. on the refractive index

easy technique, allowing to derive f_v in practical complex system, but it is line-of-sight.

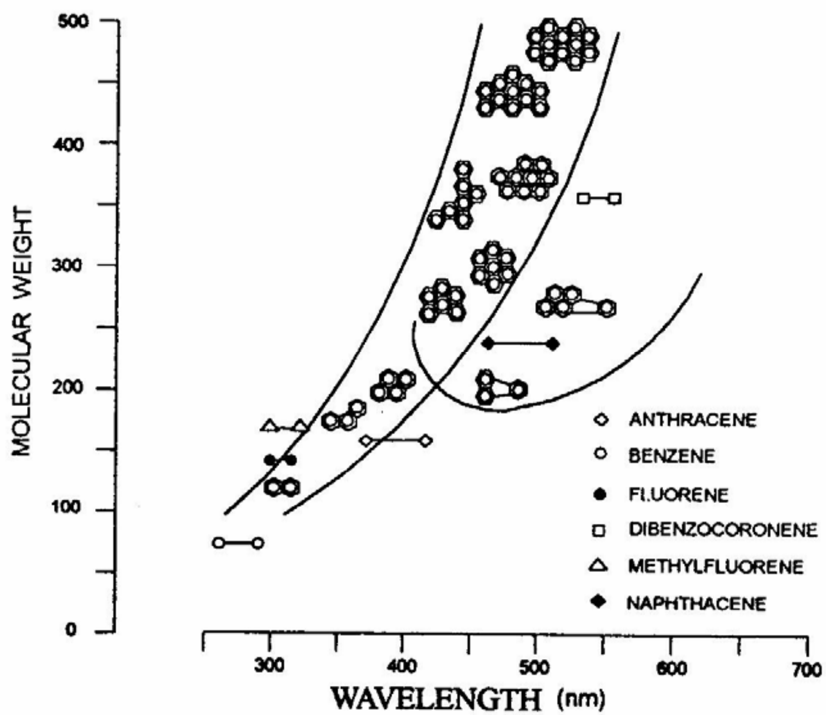
Attention to the wavelength used has to be taken: contribution of other gas-phase species to absorption is possible.

Most of the extinction measurements performed in the past with:

λ = 488 nm (Ar$^+$ laser)

λ = 632.8 nm (He-Ne laser)

Can be affected by the contribution to absorption from gas phase species, such as PAH's, or other species



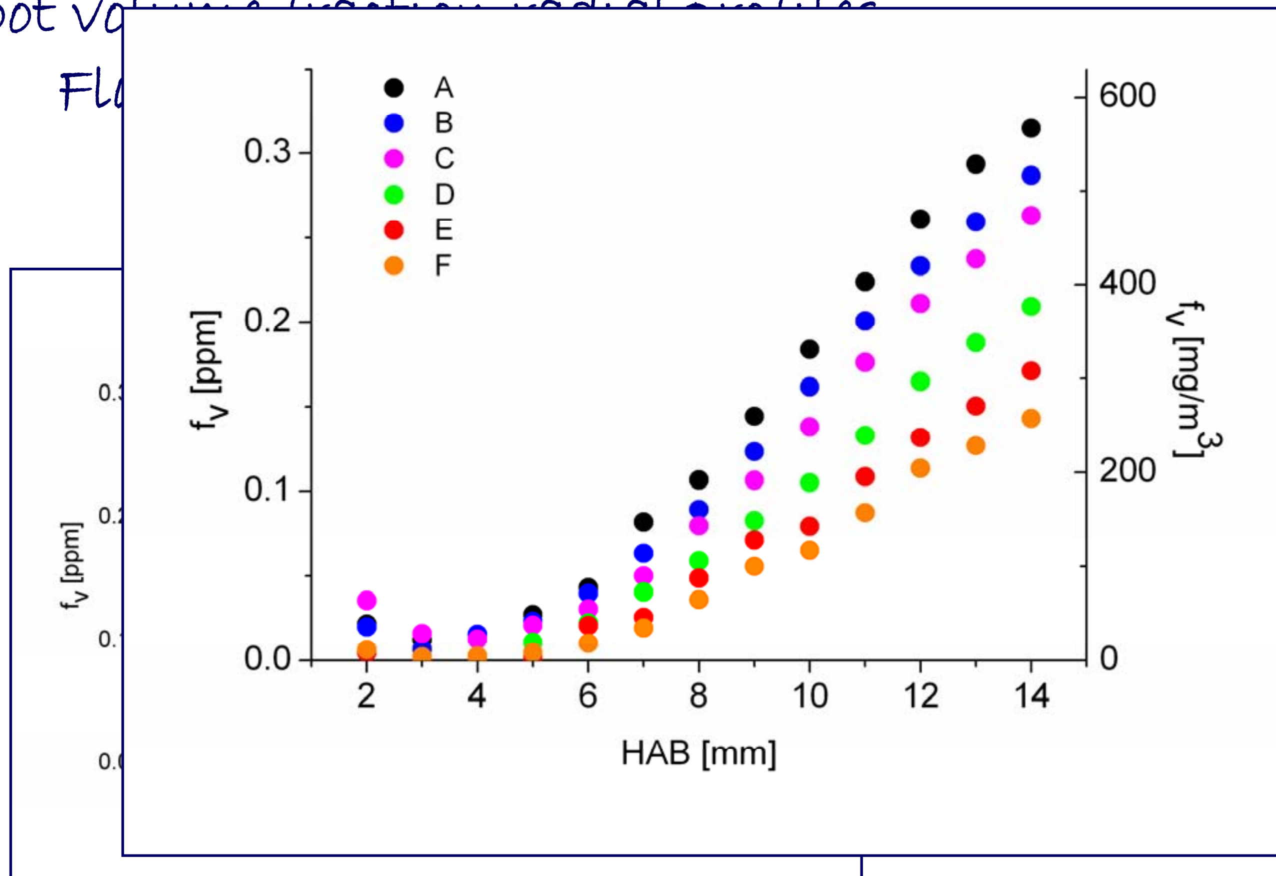
If YES ⇨ *fv* is overpredicted

We have used also the 1064 nm laser line

Soot volume fraction
($\lambda = 632.8$ nm)

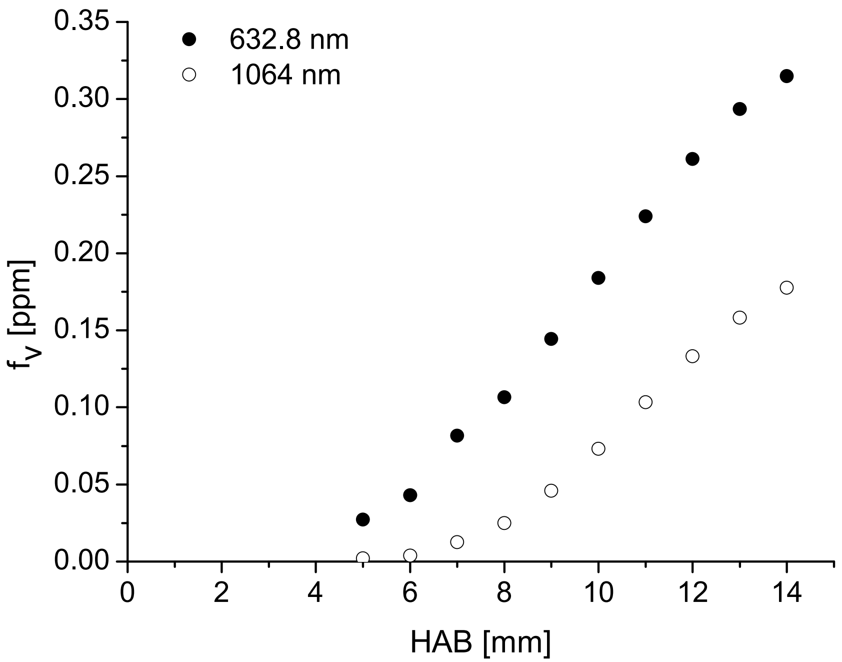
Soot vo

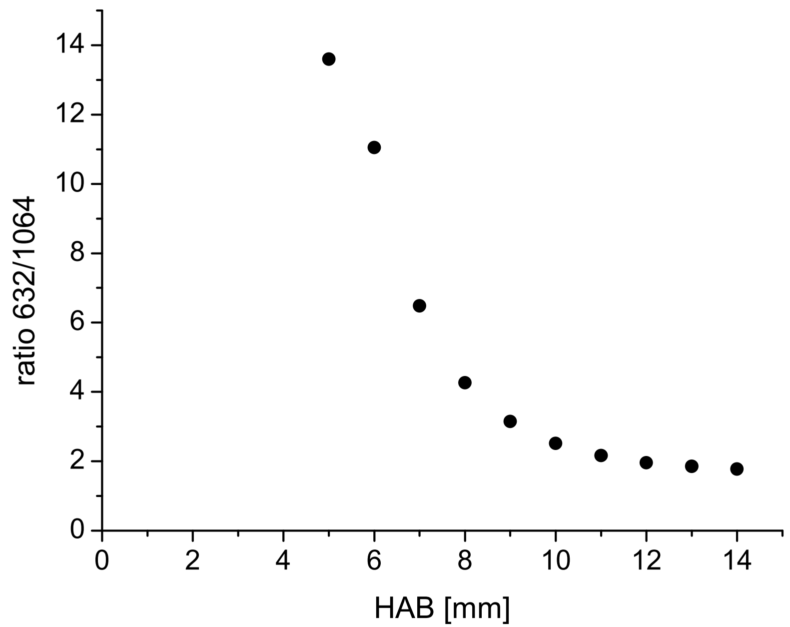
Fl



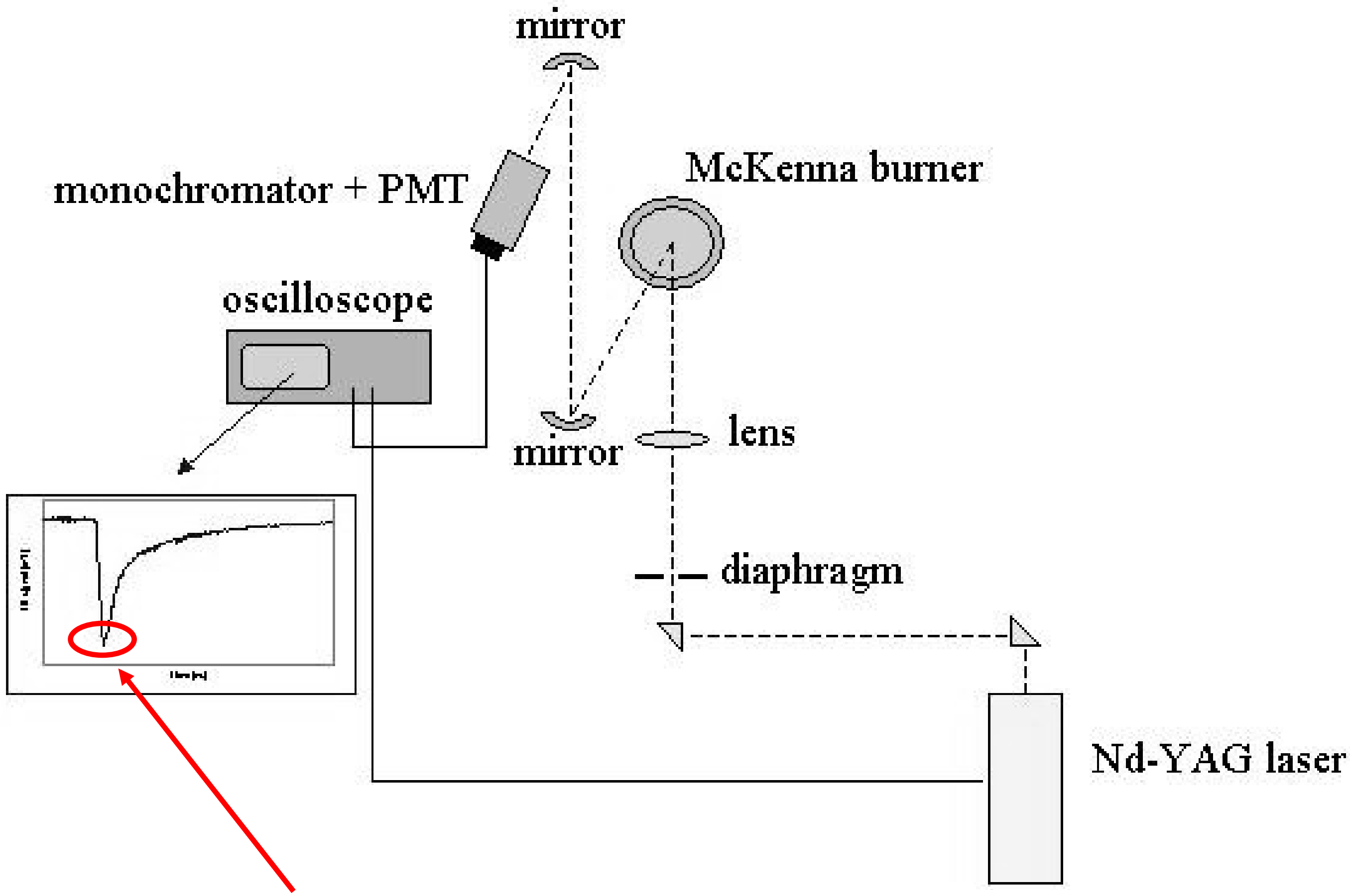
Soot volume fraction axial profiles for all the flames

Comparison of results obtained with red or IR laser (ethylene/air: Φ =2.34)



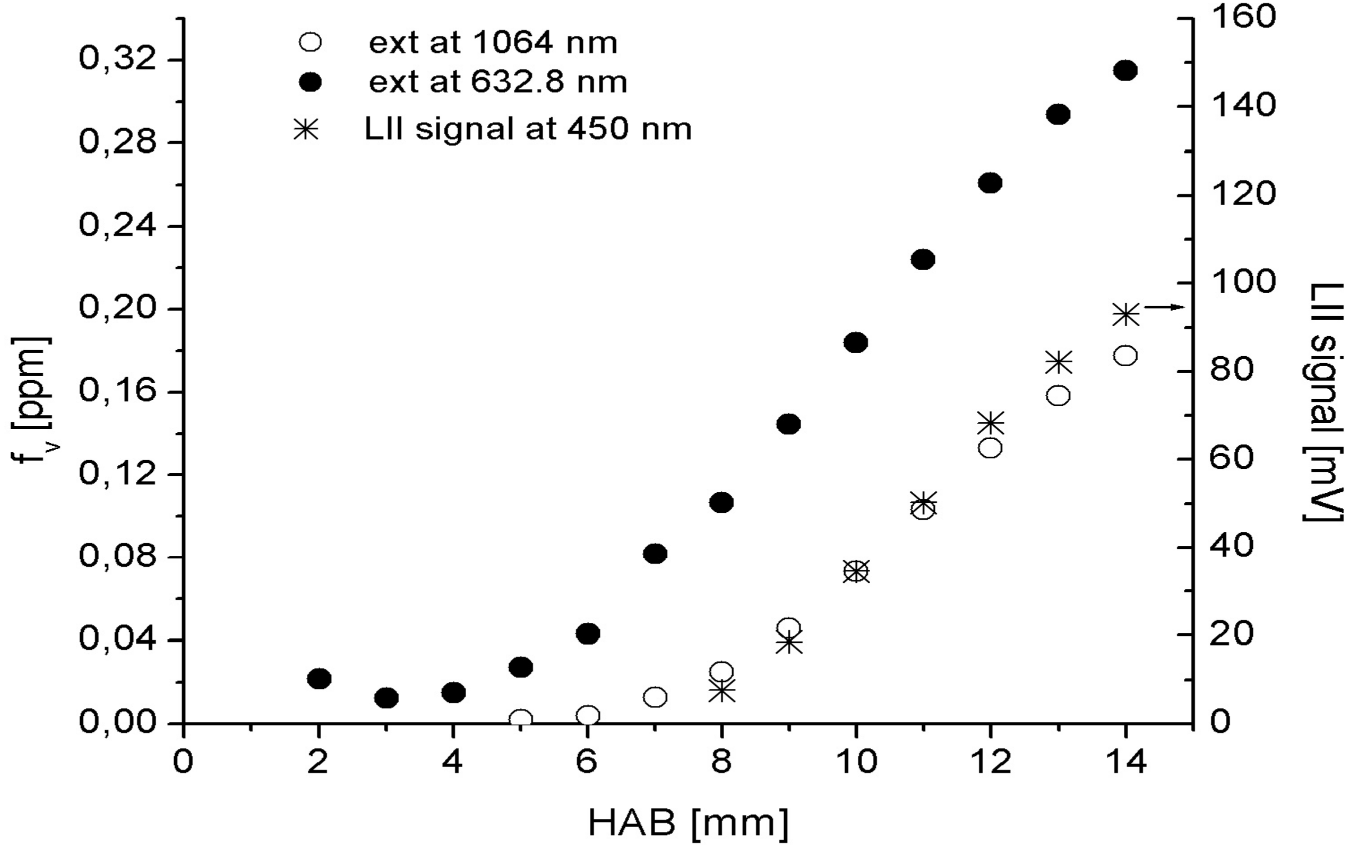


Laser Induced Incandescence (LII)



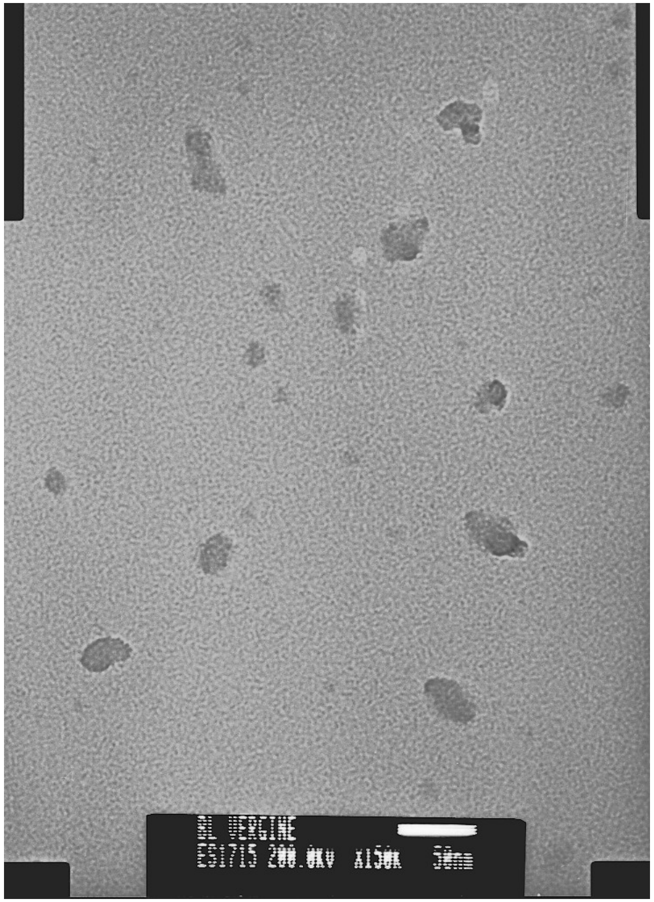
From Melton: prompt (LII) $\propto$ Np dp$^x \approx f_v$

where $x = 3 + 154\ nm/\lambda_{det}$ ⇨ is LII signal dependent on dp?

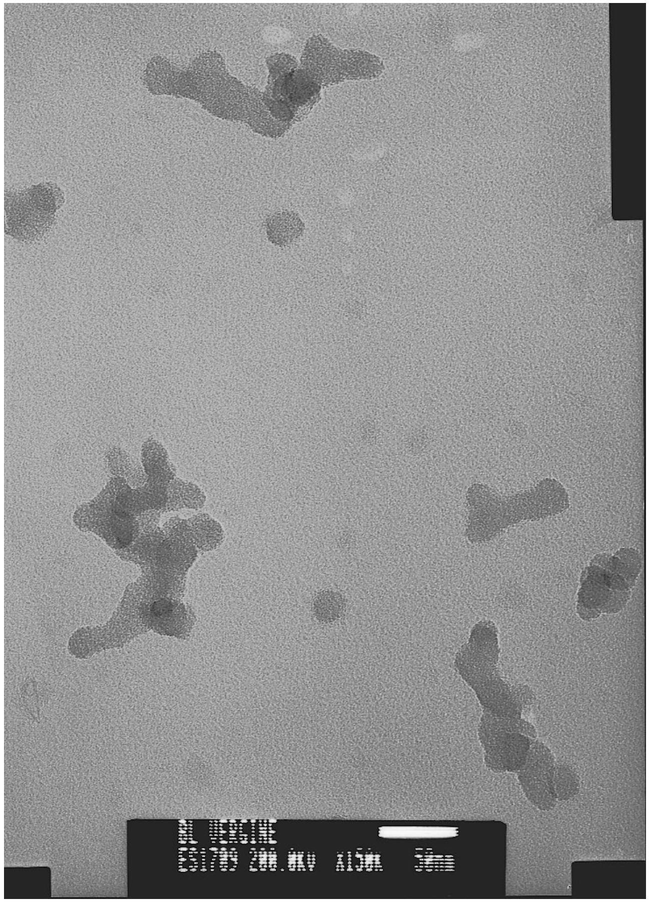

ext at 1064 nm
ext at 632.8 nm
LII signal at 450 nm
f_v [ppm]
LII signal [mV]
HAB [mm]
0,00
0,04
0,08
0,12
0,16
0,20
0,24
0,28
0,32
0
20
40
60
80
100
120
140
160
0
2
4
6
8
10
12
14

McKenna burner

Thermophoretic sampling and TEM imaging



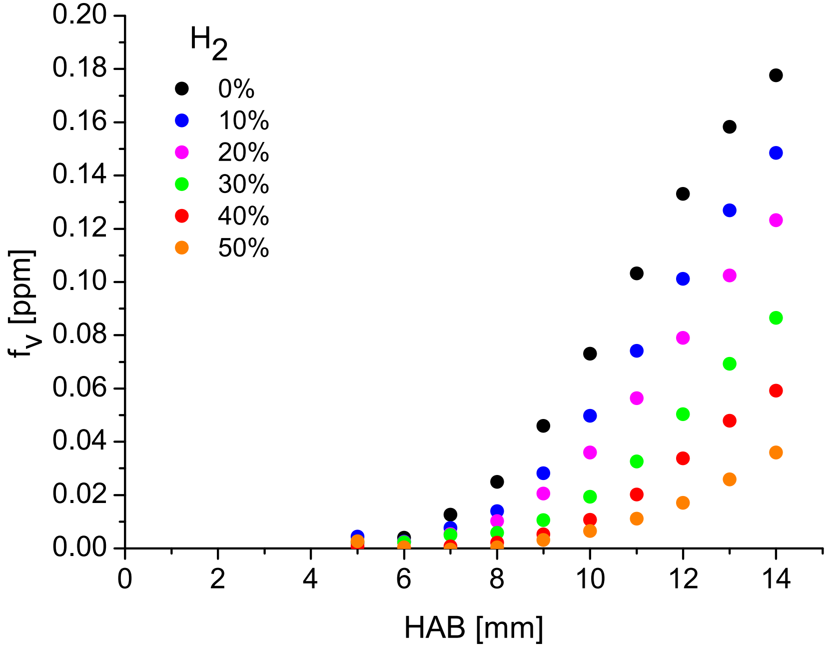
10 mm



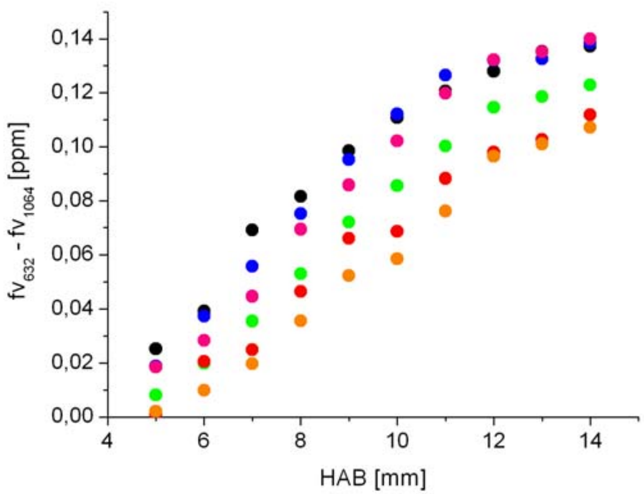
14 mm

Effects of H_2 addition

Soot volume fraction ($\lambda = 1064$ nm)

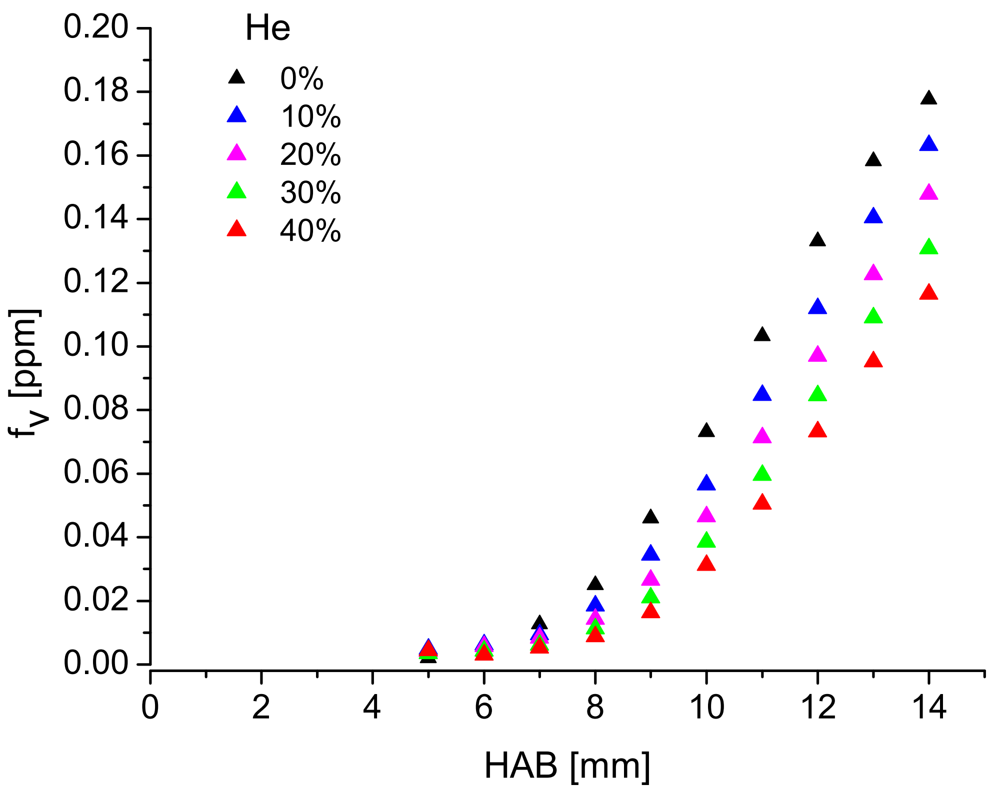


$\Delta fv_{632} - \Delta fv_{1064}$



Effects of He addition

Soot volume fraction
($\lambda = 1064$ nm)



Criterion to compare different flames

Total soot load content

Thanks to the flat structure of the flame (regular radial profiles), it is possible to estimate the total soot content for each flame, starting from the corresponding axial profile.

Volume

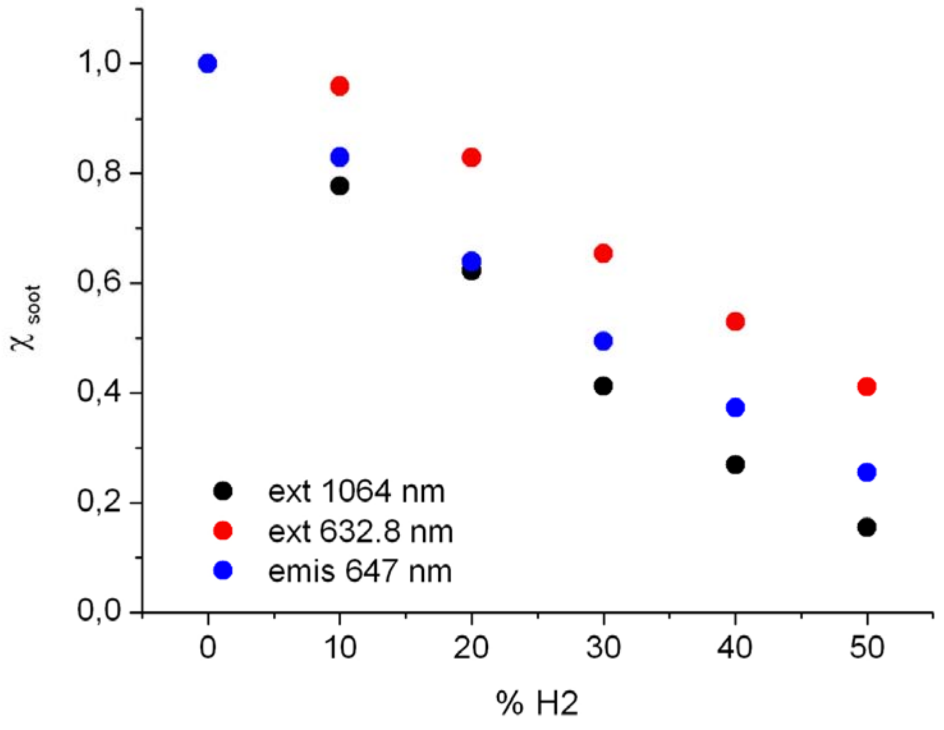
$$Soot\ load = \rho_{soot} \cdot \sum_{HAB=2}^{14} f_v(HAB) \cdot \pi \cdot \left(\frac{L(HAB)}{2}\right)^2 \cdot \Delta HAB$$

L (HAB)= flame diameter

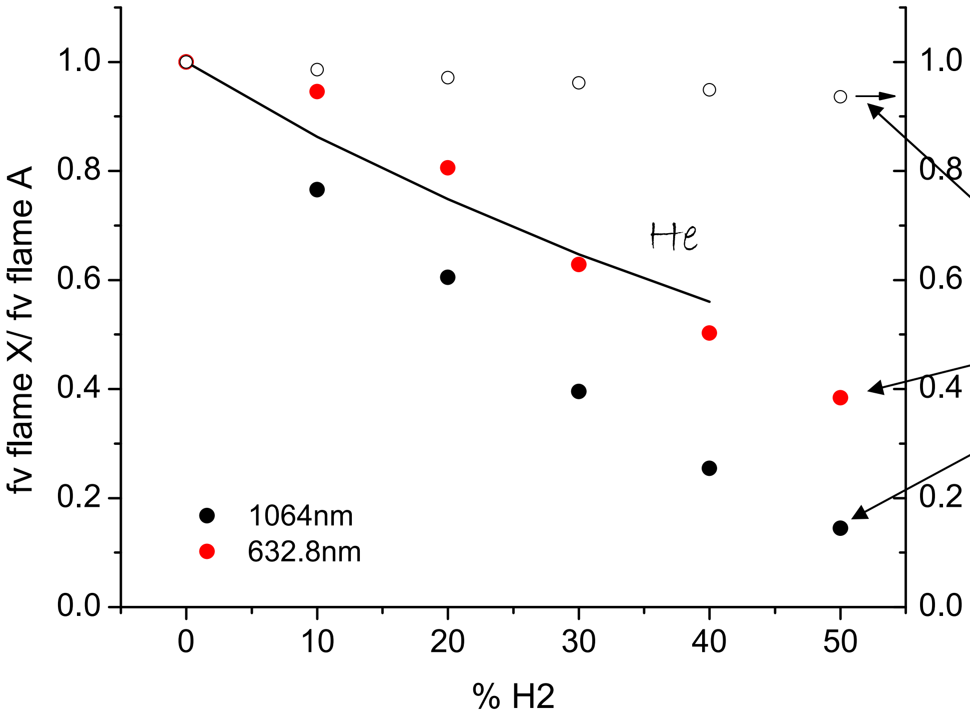
As the amount of soot is directly correlated to the amount of C atoms present in the flame, this aspect must be considered to discuss the effect of H_2 on soot production.

Influence of H_2 addition on the total soot load

Results and Comparison between techniques



Total soot load



Reduction

Ethylene : - 6.4 %

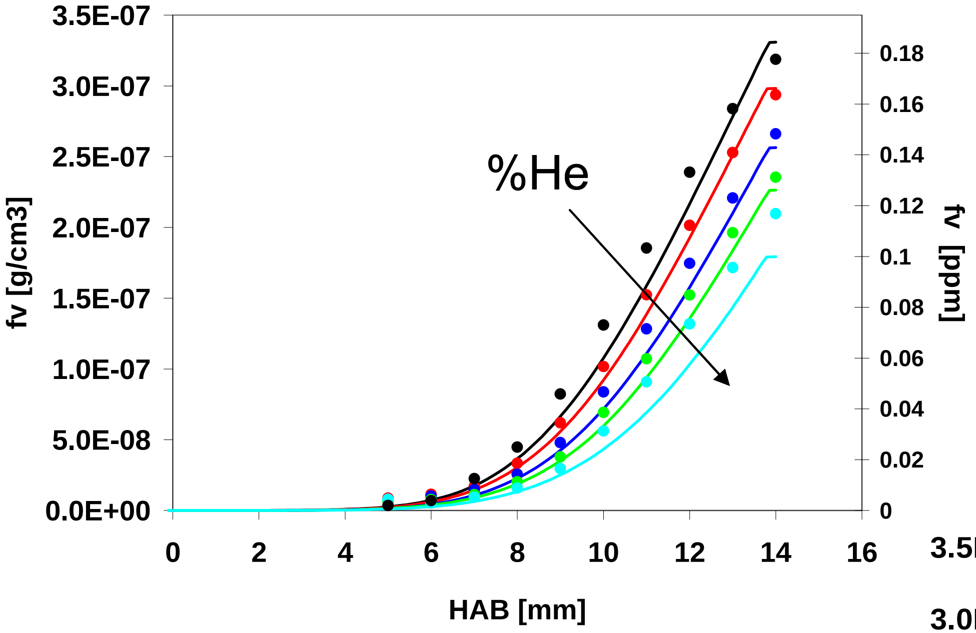
"Carbon" load : - 61.6 %

Soot load : - 85.0 %

The addition of H2 causes a decrease in soot load much higher than the decrease in ethylene fraction.

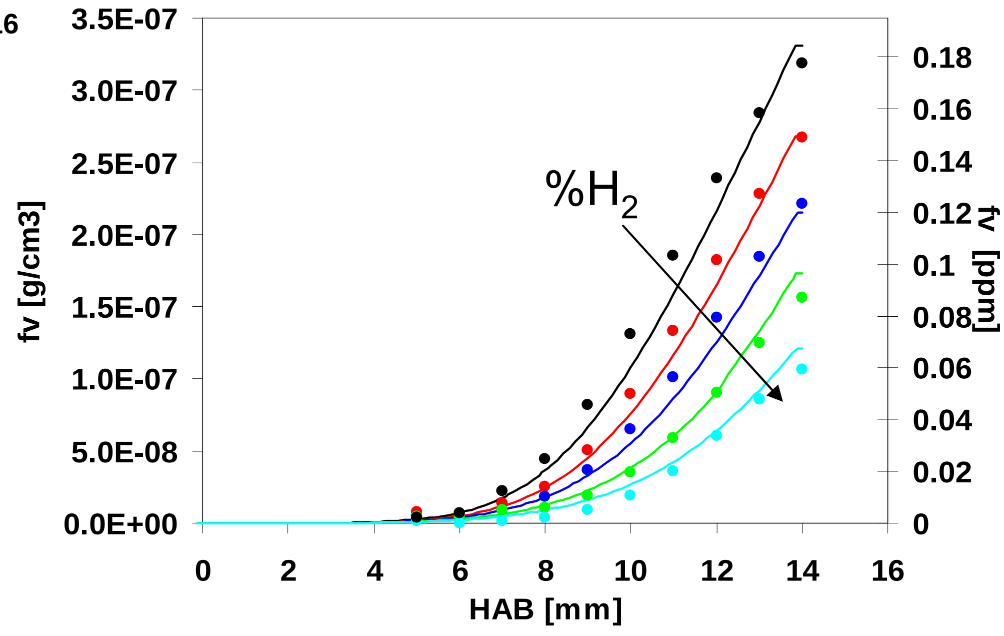
LAMINAR PREMIXED FLAMES –

Comparison with model (M. Sirignano, A. D'Anna)



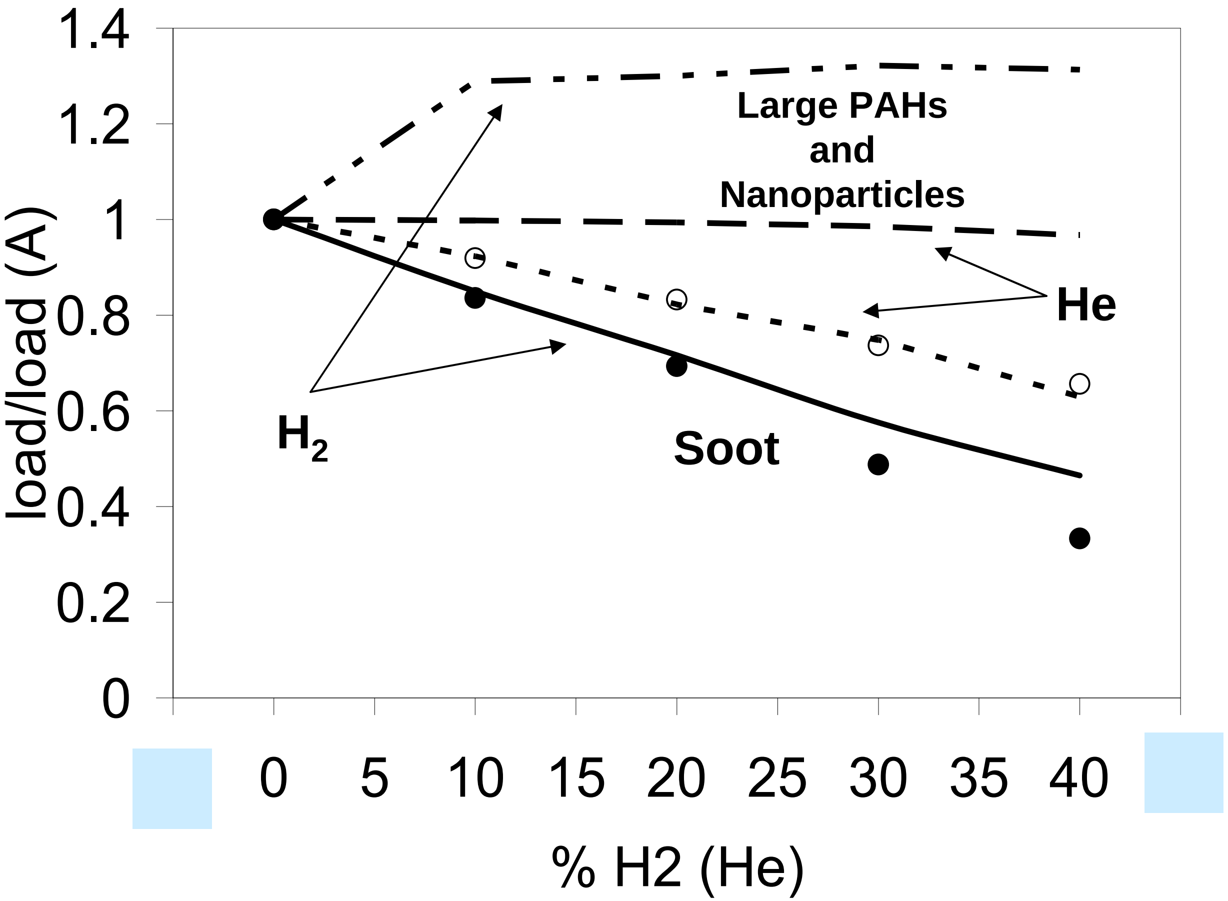
Both diluents inhibit soot formation

Soot load decrease is generally proportional to percentage of diluents



LAMINAR PREMIXED FLAMES – RESULTS

(at 14 mm height)



Reduction in soot load more evident with H_2 addition

Enhanced formation of other pollutants as PAHs and Nanoparticles with H_2 addition

Conclusions

1. In rich premixed ethylene-air flames different species are responsible for the absorption at 632.8 nm and 1064 nm. In evaluating the data, careful evaluation of the laser extinction measurements is necessary.
2. Emission measurements can also be affected by emitting species different from "mature" soot.
3. Hydrogen addition to premixed ethylene-air flames has a strong influence in reducing the total amount of soot and of "carbon species". This is due to the contribution of both a dilution and chemical effects.
4. Enhanced amount of PAHs and nanoparticles with respect to "mature" soot in H_2 flames is also found.