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Investigation of Soot Optical Properties by Spectral Line-of-Sight Attenuation

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Motivation

USA Today, Thursday, January 22, 2009 – Front Page (1A)

Cleaner air may be adding 5 months to your life
By Liz Szabo, USA TODAY

Americans are living nearly three years longer than they were only two decades ago, and they owe up to five months of that longevity to cleaner skies, a study shows.

"It is a good-news story," says Brigham Young University's C. Arden Pope, author of the study in today's *New England Journal of Medicine*, which included 51 metro areas in the USA and more than 200 countries. "Our efforts to clean up our air appear to be worth it."

All cities got a boost from cleaner air, including areas where air was relatively clean at the beginning of the study, the results show.

On average, cities reduced their pollution levels by one-third, cutting the level of small particles from 21 micrograms per cubic meter to 14 micrograms per cubic meter, the study says. At the same time, life expectancy increased by an average of 2.7 years…

http://www.usatoday.com/news/health/2009-01-21-air-pollution_N.htm?loc=interstitialskip

Optical soot diagnostics

- Non-intrusive method to measure, understand and hopefully control soot formation
  - validation for combustion and soot formation modeling
  - real-time feedback for combustor optimization
- Highly sensitive real-time diagnostic to measure and characterize soot emissions and ambient air quality

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Optical Properties in Soot Diagnostics

- Interpretation of soot optical diagnostics (i.e. from emission, scatter, or attenuation) requires knowledge of the optical properties of soot.
- Soot refractive index absorption function, E(m)
  - relevant to LOSA, LII, and multi-wavelength pyrometry

$$T = \frac{hc}{k_b}\left[\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right]\ln\left[\frac{E\left(m_{\lambda_2}\right)}{E\left(m_{\lambda_1}\right)}\frac{I_{\lambda_1}}{I_{\lambda_2}}\frac{\lambda_1^{\ 6}}{\lambda_2^{\ 6}}\right]^{-1}$$

$$f_v = \frac{K_\lambda^{(a)}\lambda}{6\pi E(m)_\lambda} = \frac{K_\lambda^{(\mathrm{e})}\lambda}{6\pi\left(1+\rho_{\mathrm{sa}}\right)E(m)_\lambda}$$

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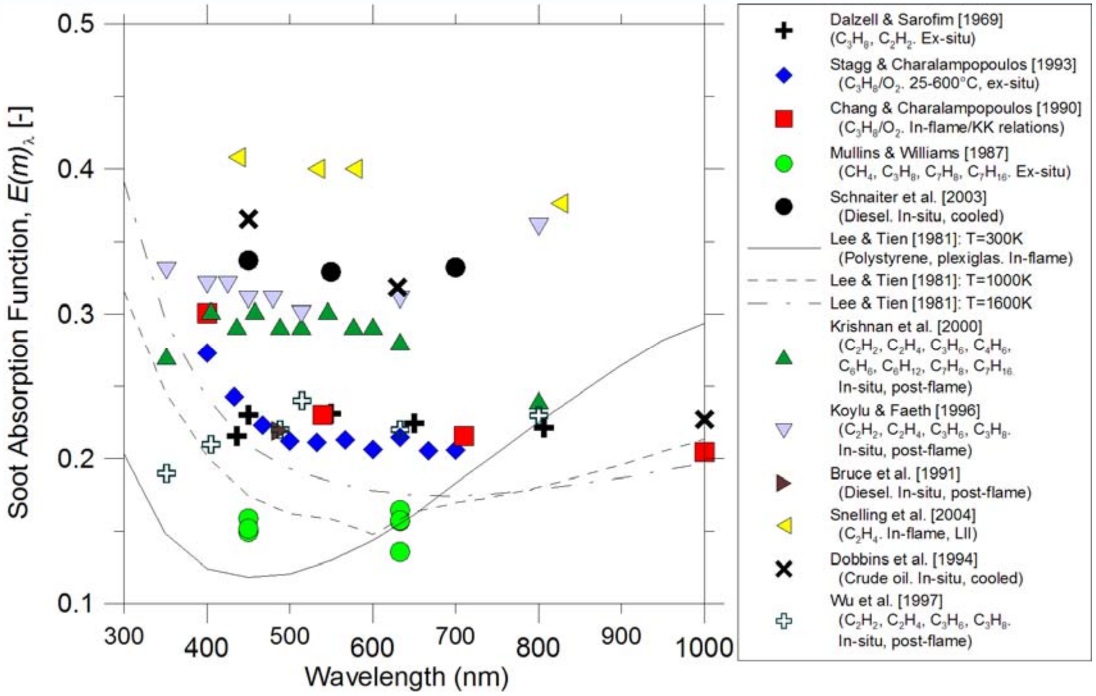
E(m) from the literature

- Even in the visible region the $E(m)_\lambda$ spread is significant!



- Moving from a slight decrease of E(m) with λ (Chang & Charalampopoulos) to an opposite slope (Krishnan et al.) the variation on *T* and f_v will be 13% and 64% respectively

Variation of $E(m)_\lambda$ with wavelength

- Ultimately want to know the *absolute* value of $E(m)_\lambda$ with λ
- Intermediate goal: *relative* variation of $E(m)_\lambda$ with λ
- Can use multi-wavelength line-of-sight attenuation (SpecLOSA) to measure the relative variation $E(m)_\lambda$

Governing equations

- transmissivity of a medium (τ_λ) can be related to the extinction coefficient of the material in the medium ($K^{(e)}_\lambda$) as:

$$\tau_\lambda = \frac{I_\lambda}{I_{\lambda,0}} = \exp\left(-\int_{-\infty}^{\infty} K_\lambda^{(\mathrm{e})} \mathrm{d}s\right)$$

- through tomographic inversion of line-of-sight transmissivity can determine the local extinction coefficient

$$-\ln \tau_\lambda(y) = \int K_\lambda^{(e)} \mathrm{d}s \rightarrow K_\lambda^{(e)}(r)$$

- if measurements performed at many wavelengths, can determine $K^{(e)}_\lambda$ as a function of wavelength

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Governing equations

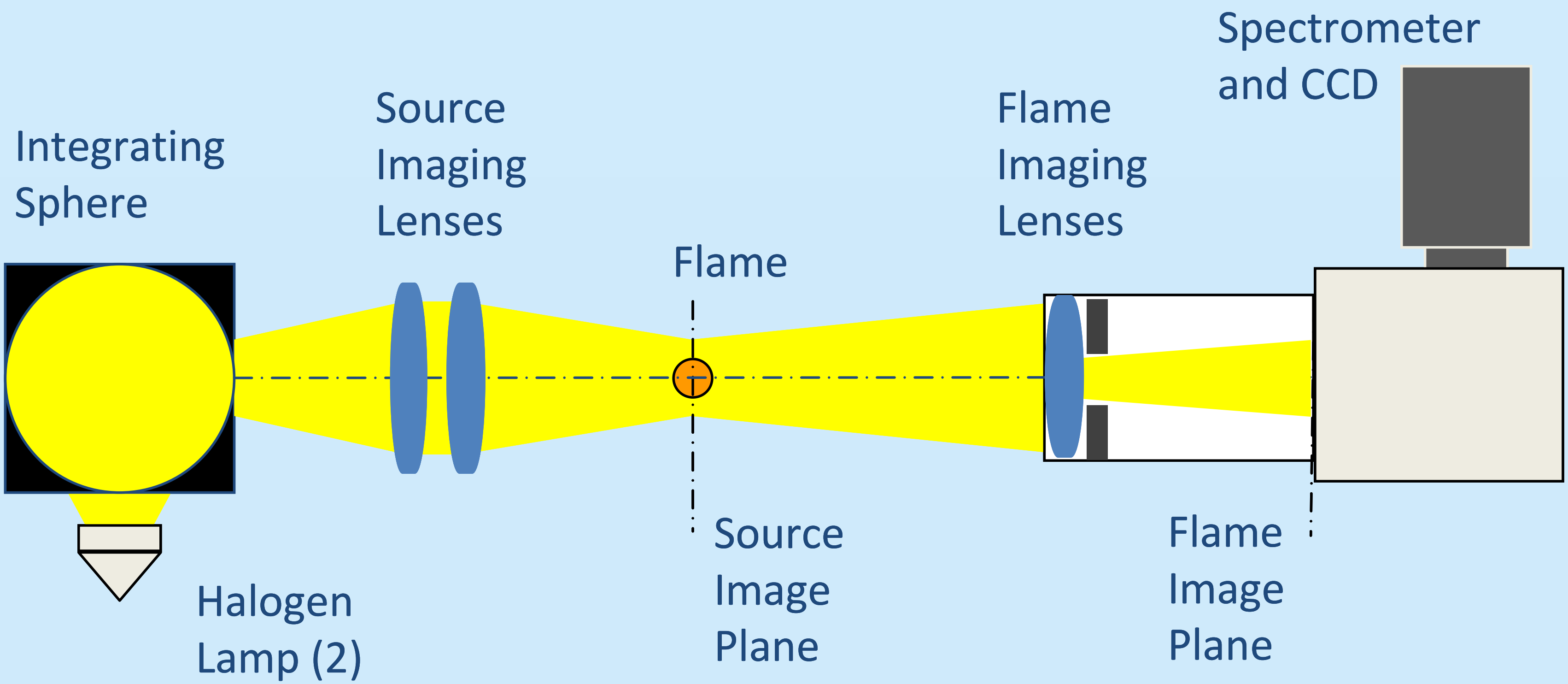
- $E(m)_\lambda$ is related to $K^{(e)}_\lambda$ via the soot volume fraction f_v as:

$$f_v = \frac{K_\lambda^{(a)}\lambda}{6\pi E(m)_\lambda} = \frac{K_\lambda^{(e)}\lambda}{6\pi\left(1+\rho_{sa,\lambda}\right)E(m)_\lambda},$$

- where, $\rho_{sa,\lambda}$ is the ratio of scatter coefficient to absorption coefficient
  - becomes close to zero for small soot aggregates and high λ
- rearranging:

$$E(m)_\lambda = \frac{K_\lambda^{(a)}\lambda}{6\pi f_v} \propto K_\lambda^{(a)}\lambda \approx K_\lambda^{(e)}\lambda = -\ln(\tau)\lambda \quad (if\ \rho_{sa} \approx 0)$$

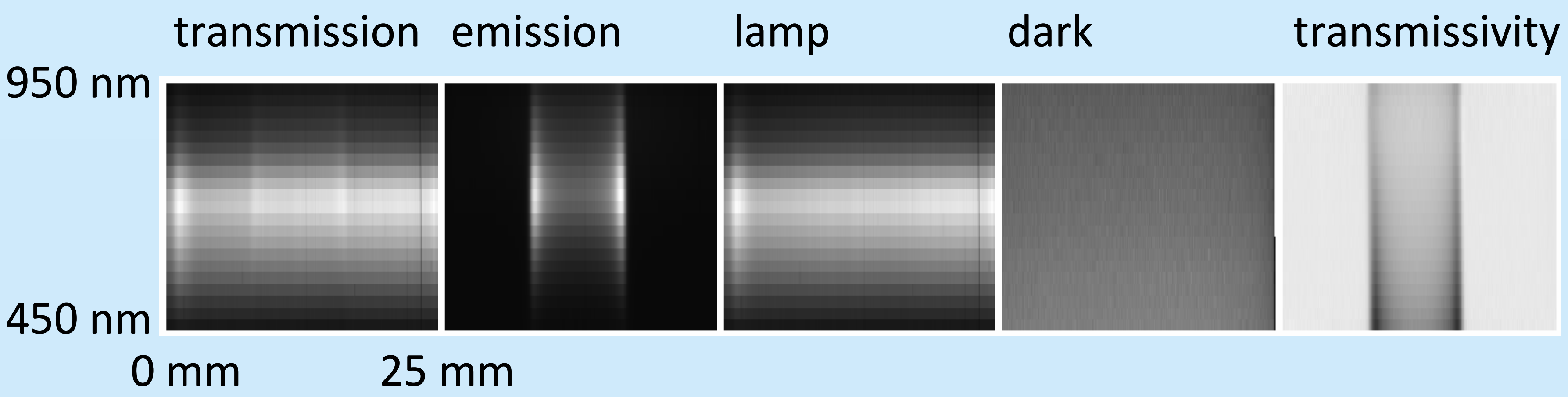
One-dimensional spectral LOSA



Gulder Burner

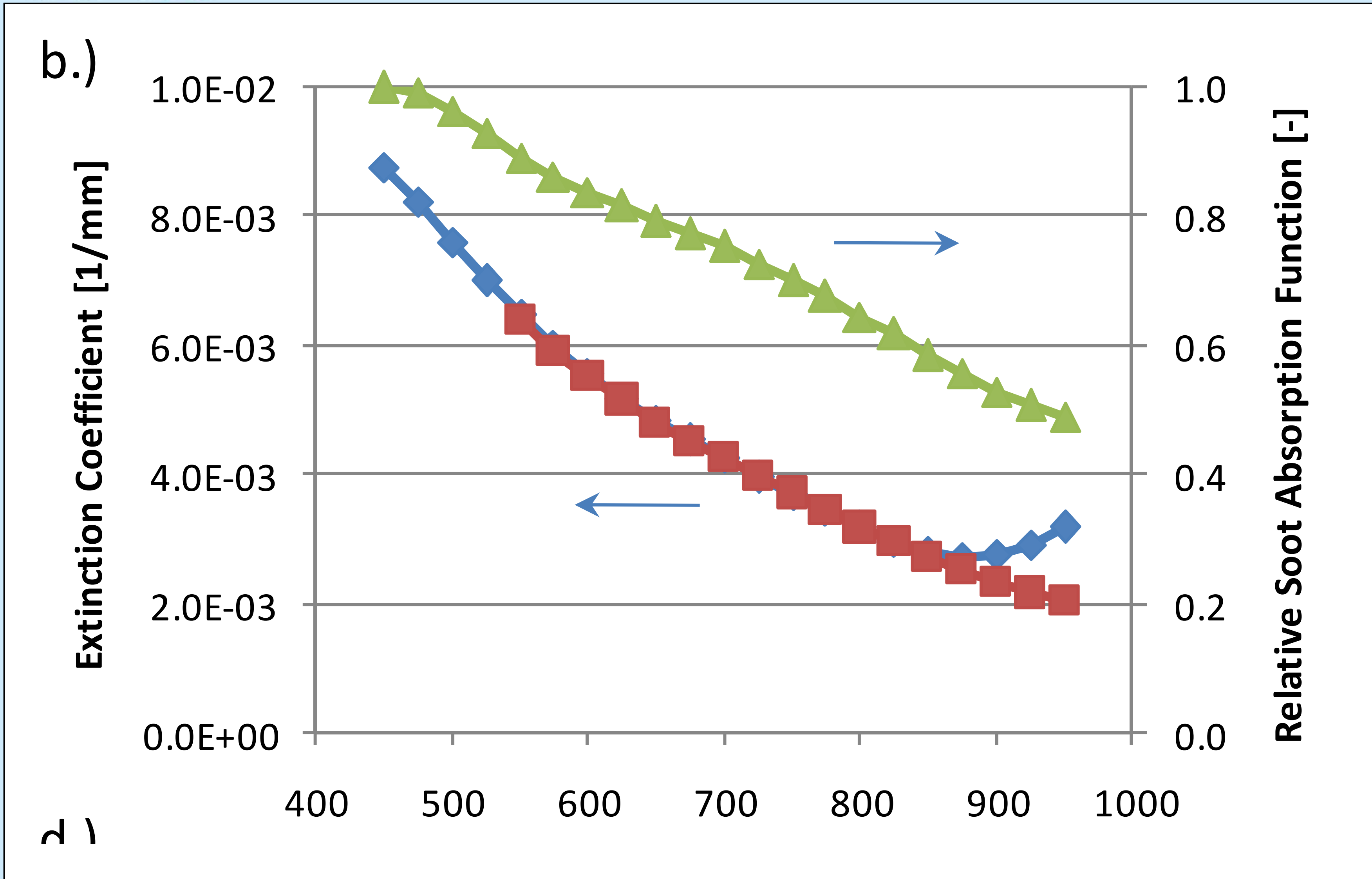
One-dimensional spec-LOSA

transmissivity = (transmission – emission)/(lamp-dark)

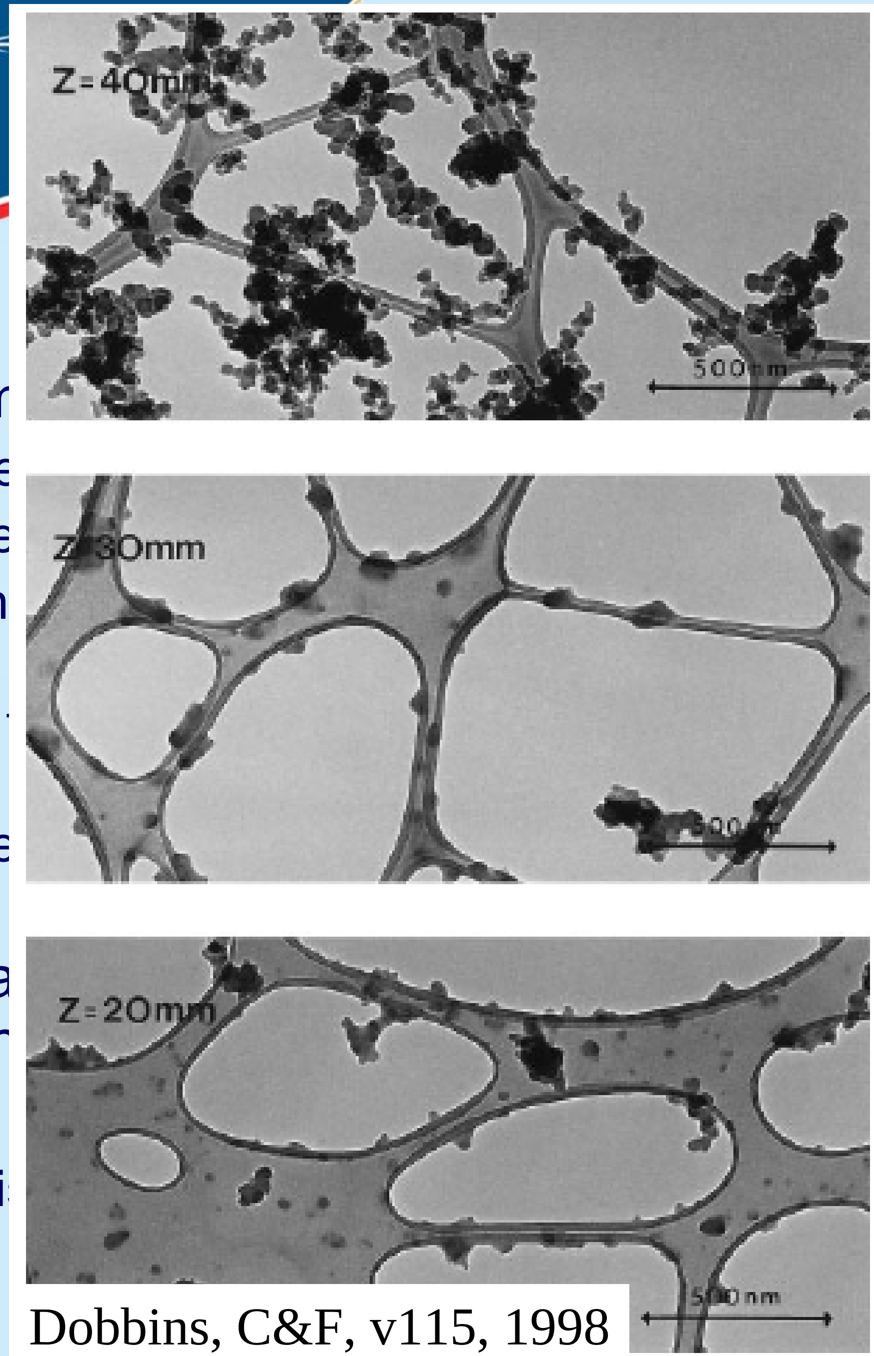


- *Applied to a Gulder non-premixed co-annular ethylene/air flame*
- *HAB = 10 mm*, 25 shot averages, binned 25 nm (v) x 50 µm (h)

$K^{(e)}_\lambda$ and Relative $E(m)_\lambda$



…on relative …der flame



Dobbins, C&F, v115, 1998

- low down in flam… …elength
  - possibly a case… …old soot
  - large PAHs are…
  - some research… …'invisible' nanoparticles
  - it seems here, … …bove which curve 'flattens'…
  - however, highe…
    - mature soot…
- critical for soot a… …surement highly dependen…
- impact for laser…
  - upon heating, i… …AH destroyed or not heated)?

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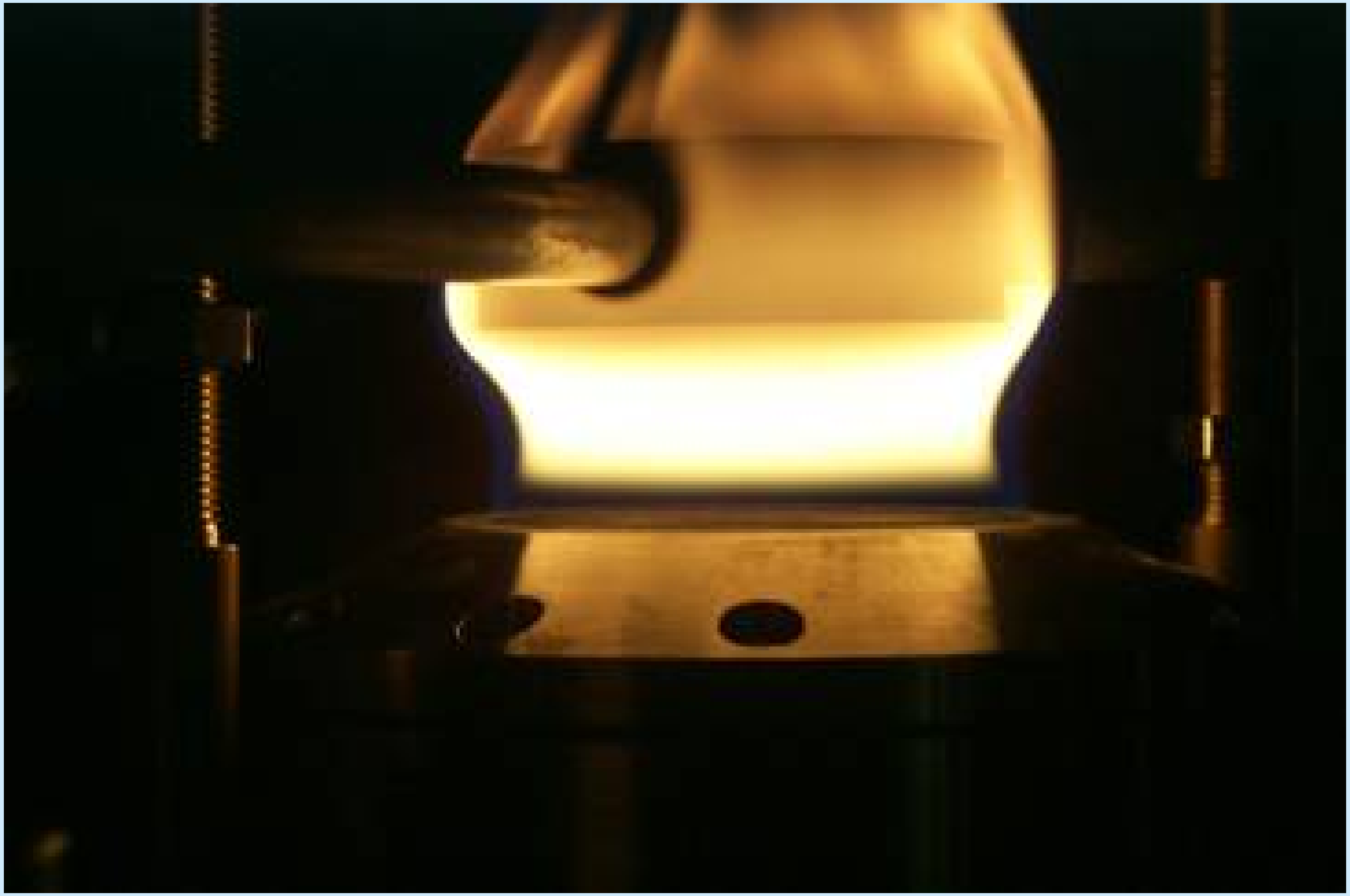
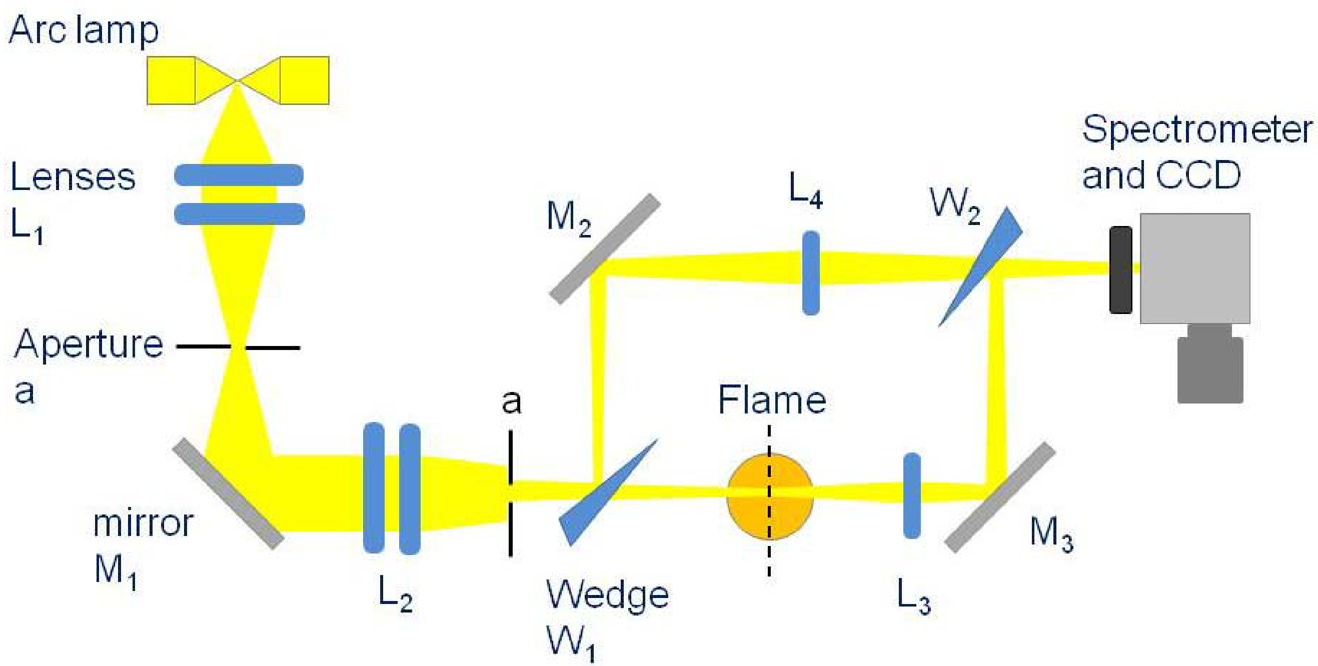
McKenna burner



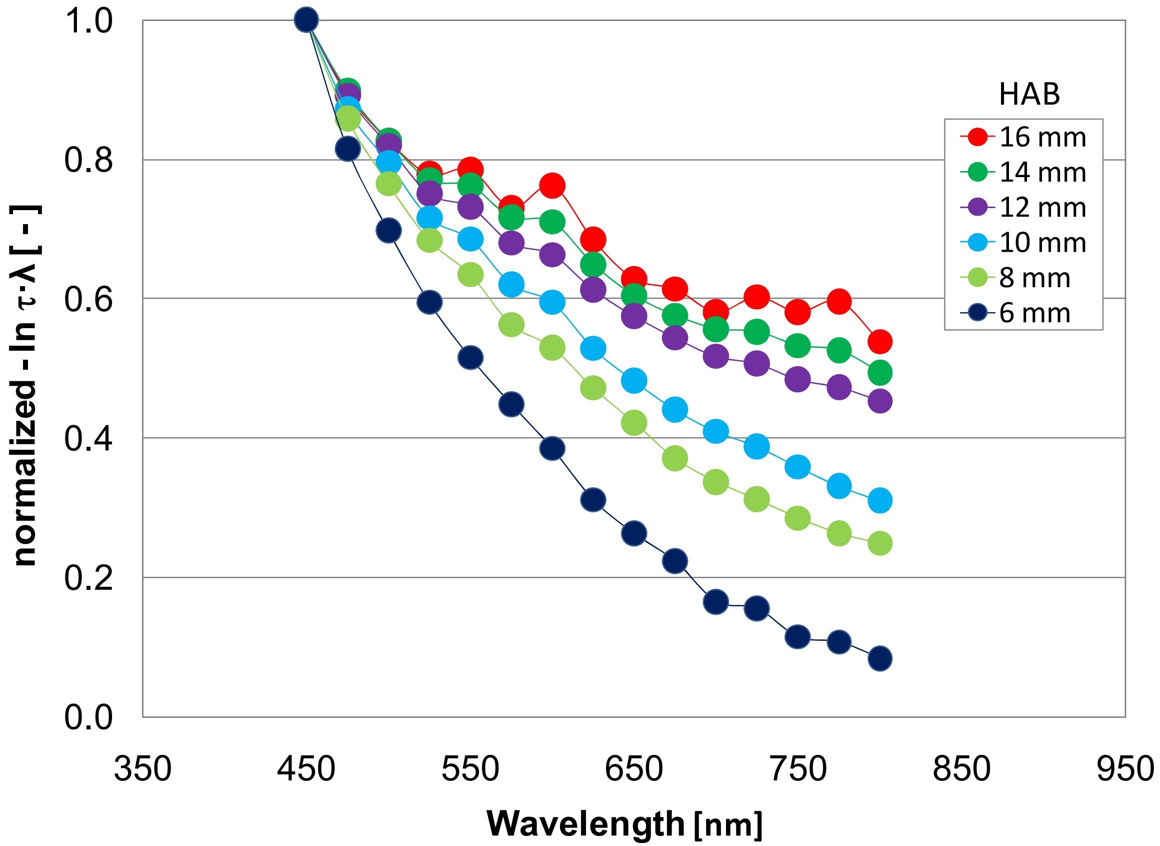
Zero-dimensional spectral LOSA

- One-dimensional Spec-LOSA cannot currently be applied in large flames
- Zero-dimensional (single line-of-sight) method developed for such flames



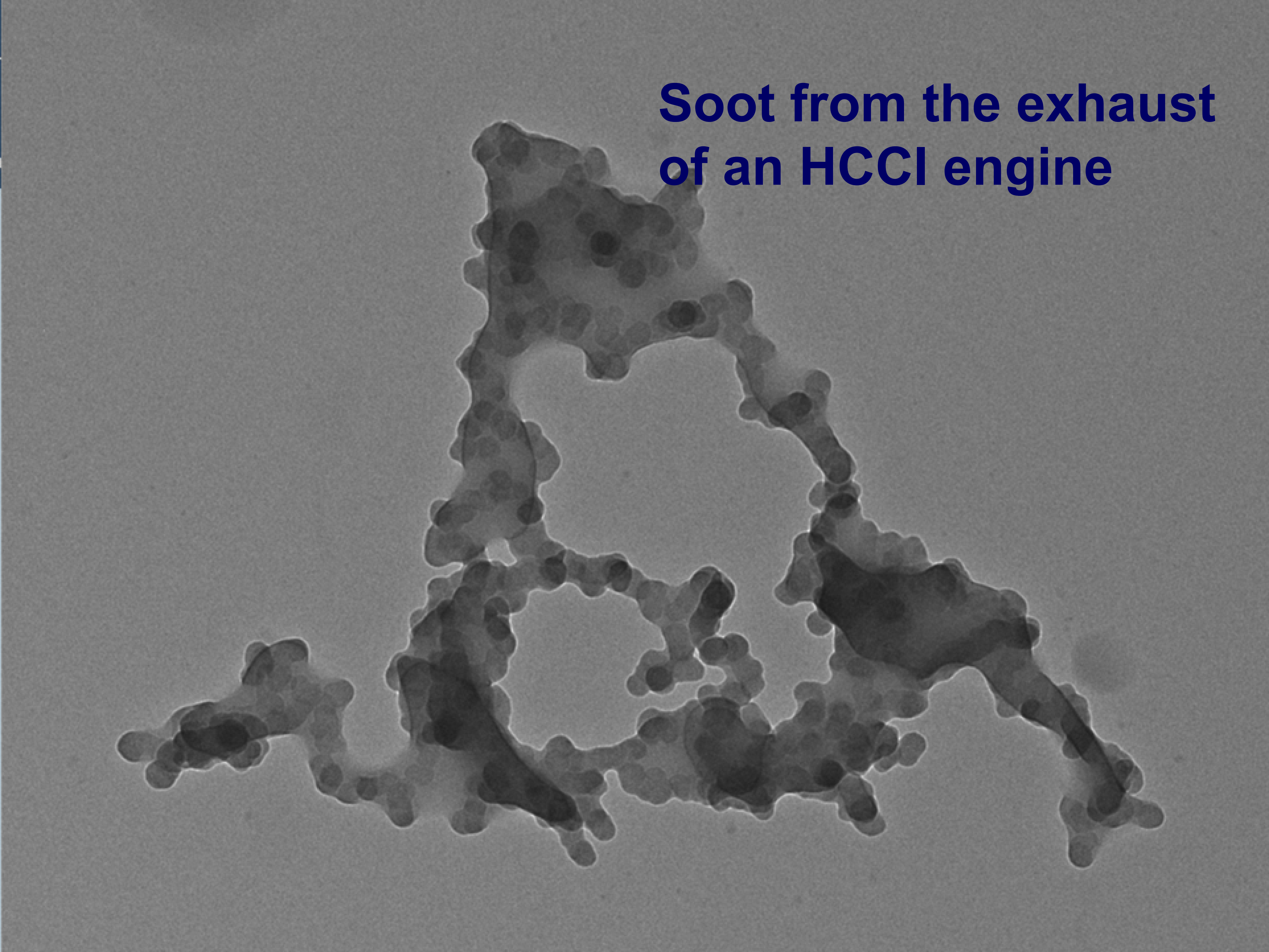
Relative $E(m)_\lambda$ for McKenna burner

$$\int K_\lambda^{(e)} \mathrm{d}s\,\lambda$$



Discussion on relative $E(m)_\lambda$ in McKenna flame

- throughout flame, $E(m)_\lambda$ <u>is highly</u> variant with wavelength
  - again, part (and likely majority) of the attenuation is not coming from soot
    - running under fuel rich condition ($\varphi = 2.1$) significant unburned hydrocarbons post flame-front
    - not dissimilar from HCCI or PPC
  - $E(m)_\lambda$ varies across all wavelengths
    - is it possible that PAH attenuates at 950 nm?
    - alternatively is variation a feature of the soot itself (higher H/C ratio)
  - either way, interpretation of LOSA, Soot Emission, LII, FSN is very challenging
    - would <u>under predict</u> soot emission based on FSN


Soot from the exhaust of an HCCI engine

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Summary and Future Work

- in mediums where unburned fuel exists, $E(m)_\lambda$ reasonably constant with λ
  - some uncertainty for $\lambda > 750$ nm which needs further examination
- otherwise, $E(m)_\lambda$ stronger in the UV (~becoming transparent in visible)
- need to clarify soot versus non-soot attenuation to correctly quantify f_v
  - relevant to all optical soot diagnostics
- need to understand how not soot absorbers impact LII measurements
  - do they participate?

Summary and Future Work

- thermophoretic sampling at measurement locations in Gulder and McKenna burner to establish morphology and aging of soot
- LII to determine sensitivity of LII to non-soot material
- emission measurements to determine if multi-wavelength pyrometry agrees with multiwavelength attenuation

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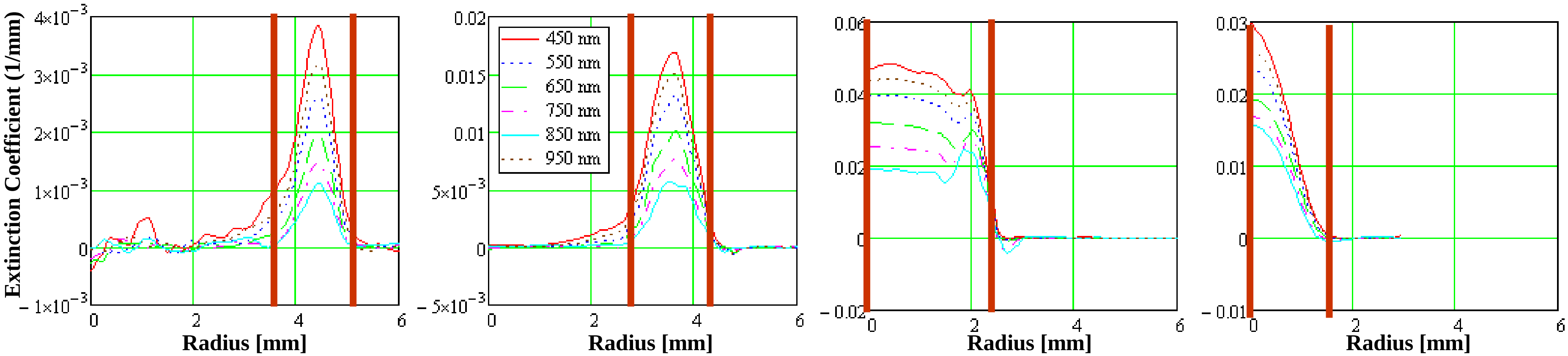
One-dimensional spec-LOSA

HAB = 5 mm | HAB = 10 mm | HAB = 42 mm | HAB = 55 mm



- extinction coefficients averaged over the sooting region at each height of the flame
  - averaging region indicated by red lines