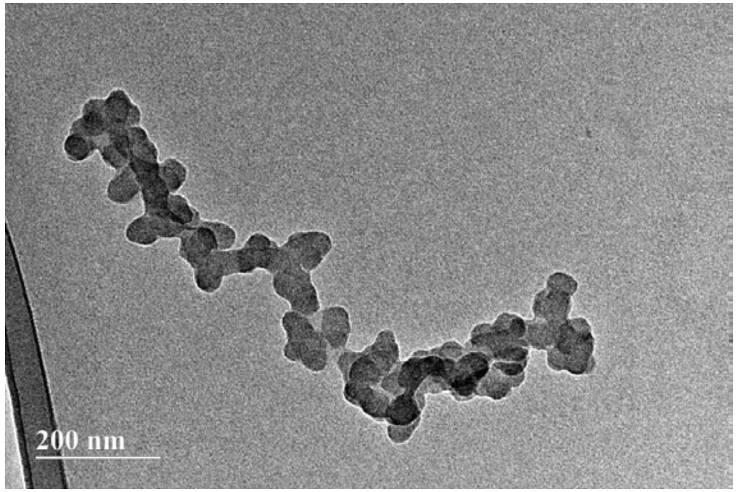
Soot and Radiation



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V. Lecoustre, L. Li, J. Maun, NASA, NIST, NSF

What is soot?

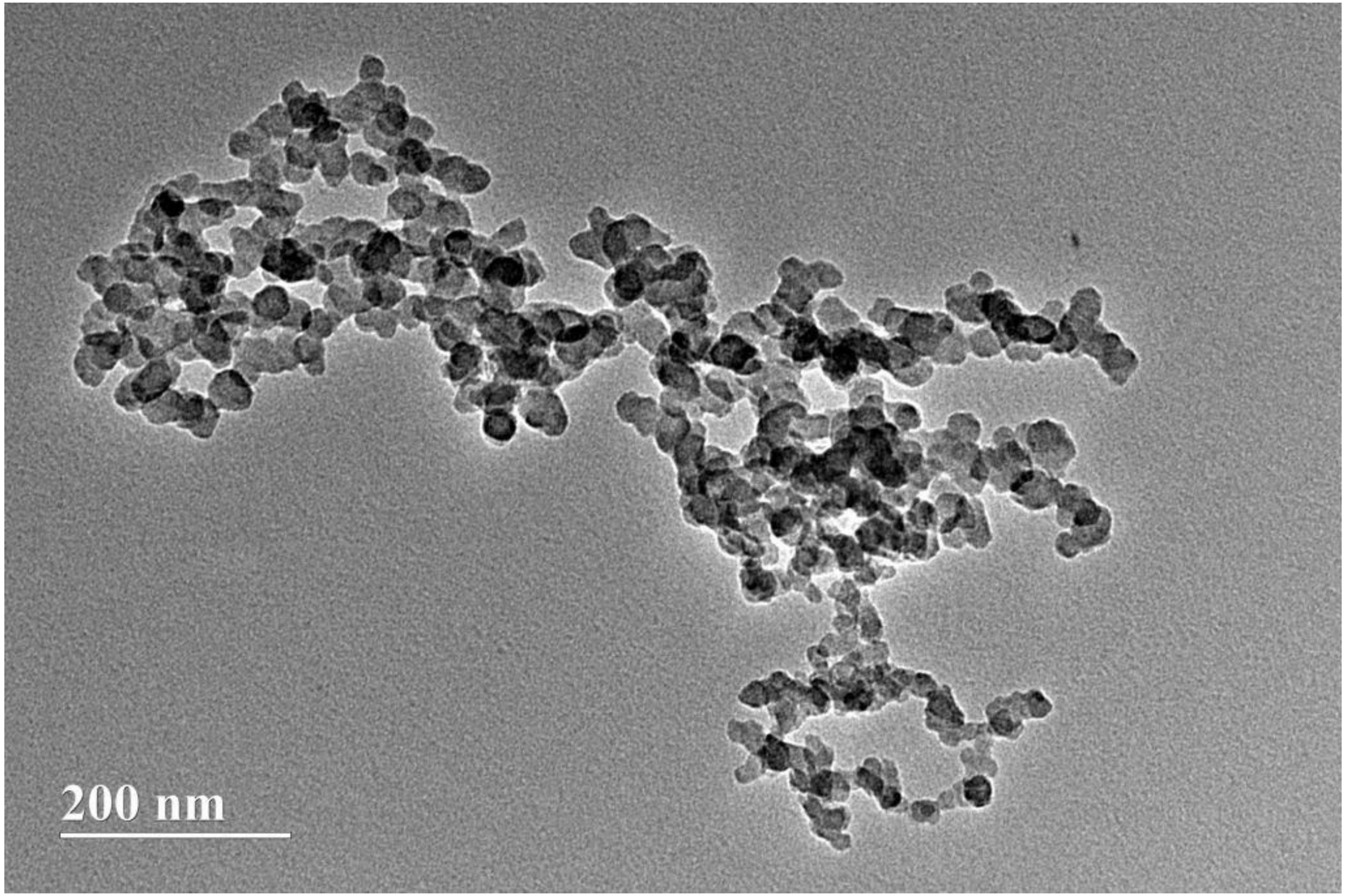
Soot: small solid carbonaceous solids formed in gas-phase flames.

Pyrogenic carbon, aka black carbon: soot, char, and biochar.

Char: solid pyrogenic carbonaceous solids resulting from incomplete combustion.

Biochar: char made from waste biomass for soil amendment and carbon sequestration.

What is soot?



Anderson (2019)

What is smoke?

Smoke: visible materials emitted from a fire.

Most smoke consists of soot (black), oil droplets (blue), water droplets (white), char (black), and ash (white or gray).

Soot and char are black
wikipedia

Oil droplets are blue
wikipedia

Water droplets and ash are white
New York Times

Health and environmental impacts

The New York Times

SATURDAY, APRIL 21, 2001

TINY BITS OF SOOT TIED TO ILLNESSES

E.P.A. Finds the Strongest Link Yet to Support Restrictions

By ANDREW C. REVKIN

NATURE | VOL 409 | 8 FEBRUARY 2001 | www.nature.com

news and views

The dark side of aerosols

Meinrat O. Andreae

According to new modelling calculations, black carbon in the atmosphere exerts a large warming influence on global climate. Curbing emissions of this pollutant may be advisable both on climate and on human health grounds.

letters to nature

Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols

Soot in fires

Hickory Record, 2013

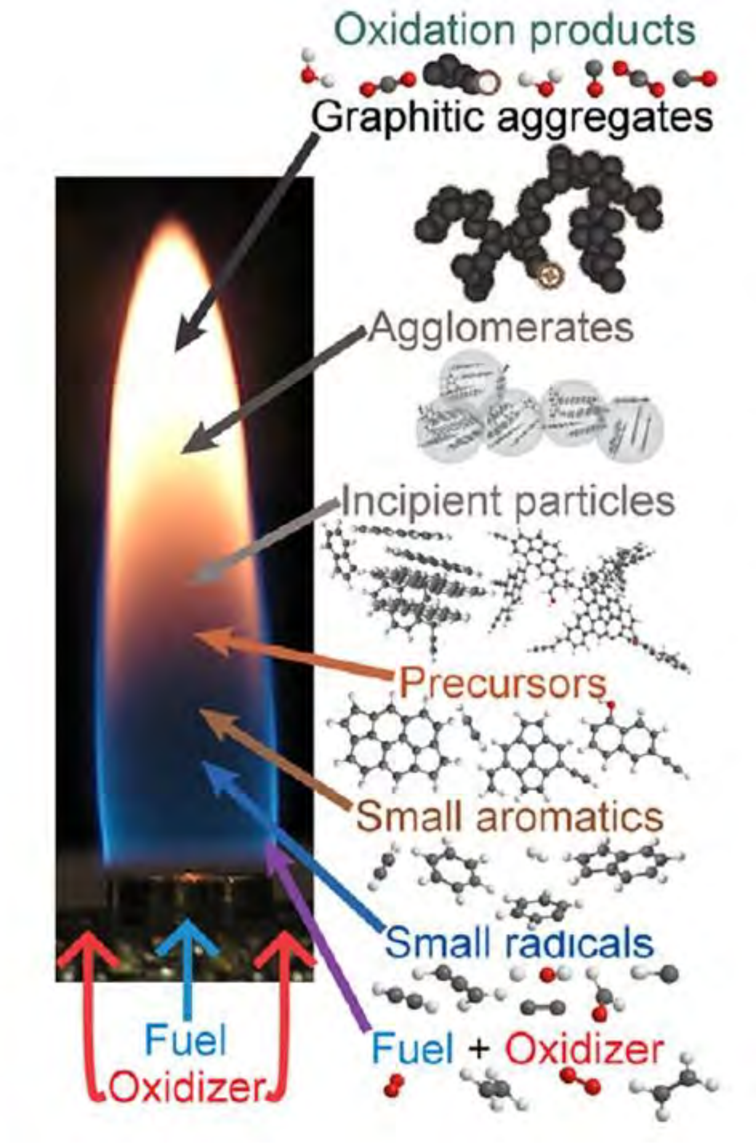
- Most fire deaths are associated with smoke inhalation, not burns.
- Soot emission is associated with CO emission.
- In many fires radiation is the dominant mode of heat transfer and is dominated by soot.
- Numerical fire models rely on accurate and simple soot models.

Soot benefits and hazards

Benefits	Hazards
Radiation in boilers	60,000 US deaths annually
Rubber additive	Cytotoxic, carcinogenic
Printer toner	CO emission
Pigments	Climate change
Lubrication	Fire spread
Filtration	Fire obscuration
Candles	Property damage
	Radiation in engines

“Soot formation is one of the most complex phenomena in combustion, involving complicated interactions between combustion chemistry, fluid mechanics, mass/heat transport, and particle dynamics, so that despite decades of active research, many gaps still remain in our understanding of soot.” (Wang and Chung, PECS 2019).

Soot chemistry



Oxidation

Aggregation

Growth. Agglomeration, coagulation, dehydrogenation, solidification. Primary particles with d = 10 – 50 nm, C/H = 10 – 20.

Nucleation. Aka nascent particles or nano-organic carbon. Can be disordered (if lean) or stacked (if rich). Liquid-like. C/H = 1.4 – 2.5 and d = 1 – 6 nm.

Precursor formation, aka PAH

e.g., OH, O, H, CH, CH_2, C_2H_2

e.g., heptane and air

Michelson (PCI 2017)

Soot chemistry: nucleation

- Acetylene as a surrogate for soot nucleation is reasonably accurate. There are three widely used models:

$$J_{Moss} = 6 \times 10^6 \bar{\rho}^2 N_A \sqrt{T}\, exp\left(\frac{-46100}{T}\right) X_{C_2H_2}$$

$$J_{Leung} = \frac{2}{C_m} N_A 1.7\, exp\left(\frac{-7548}{T}\right) C_{C_2H_2}$$

$$J_{Fairweather} = \frac{2.7 \times 10^6}{\rho_s C_m} N_A\, exp\left(\frac{-46100}{RT}\right) C_{C_2H_2}$$

Wang et al. (Energies 2019)

Soot chemistry: growth

- About 90% of the soot mass comes from growth, not nucleation.
- The simplest model is Leung et al. (CST 1991):

$$\omega_\mathrm{g} = k_\mathrm{g}(T)[\mathrm{C_2H_2}]\sqrt{\pi\left(\frac{6M_C}{\pi\,\rho_C}\right)^{2/3}}[\mathrm{C}]^{1/3}(\rho N)^{1/6}$$

- For improved accuracy the HACA (hydrogen-abstraction carbon addition) is often used. Frenklach and Wang (PCI 1991):

$$\mathrm{C_{soot}{-}H + H \rightarrow C_{soot}\cdot + H_2}$$

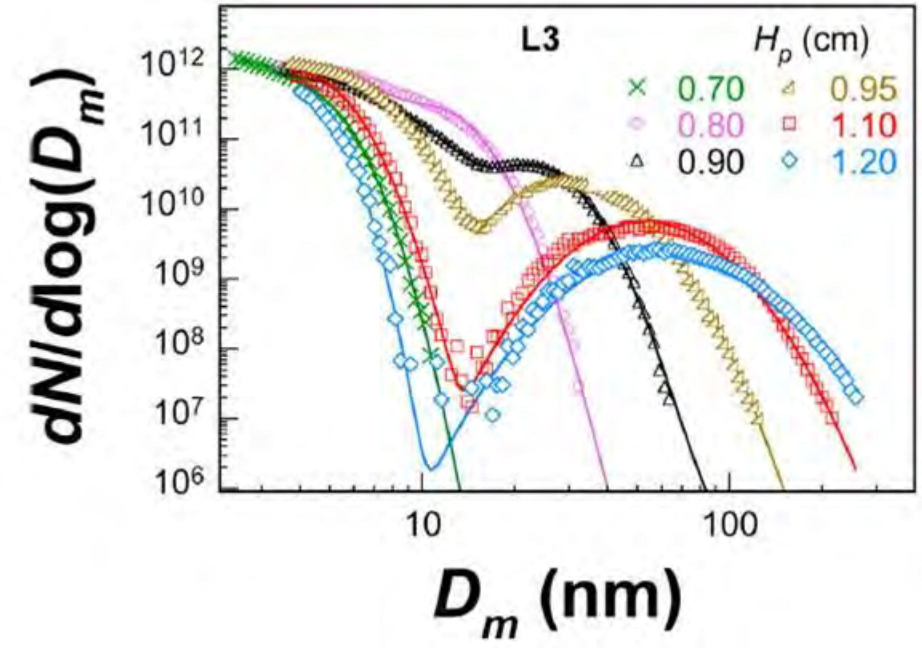
$$\mathrm{C_{soot}\cdot + H \rightarrow C_{soot} - H}$$

$$\mathrm{C_{soot}\cdot + C_2H_2 \rightarrow C_{soot}{-}H + H}$$

- Whether soot surface growth via PAH is important is a hot topic of debate.

Soot chemistry: primary particle size

- Soot surface area controls the growth and oxidation rates, and the radiative and thermophoretic behavior.
- Monte-Carlo methods are the most accurate (and costly).
- Sectional methods track the number of soot primary particles in each of ~50 size bins.
- The method of moments of the particle size distribution function can accurately reproduce the PSD with 3 – 6 moments.
- Bimodal PSDs are common.



Gu et al. (CNF 2016)

Soot chemistry: oxidation

- Soot is mostly oxidized in flames by OH and O_2, with smaller contributions from O, H_2O, and CO_2:

  C_{soot} + OH → CO + products

  C_{soot} + O_2 → 2 CO + products

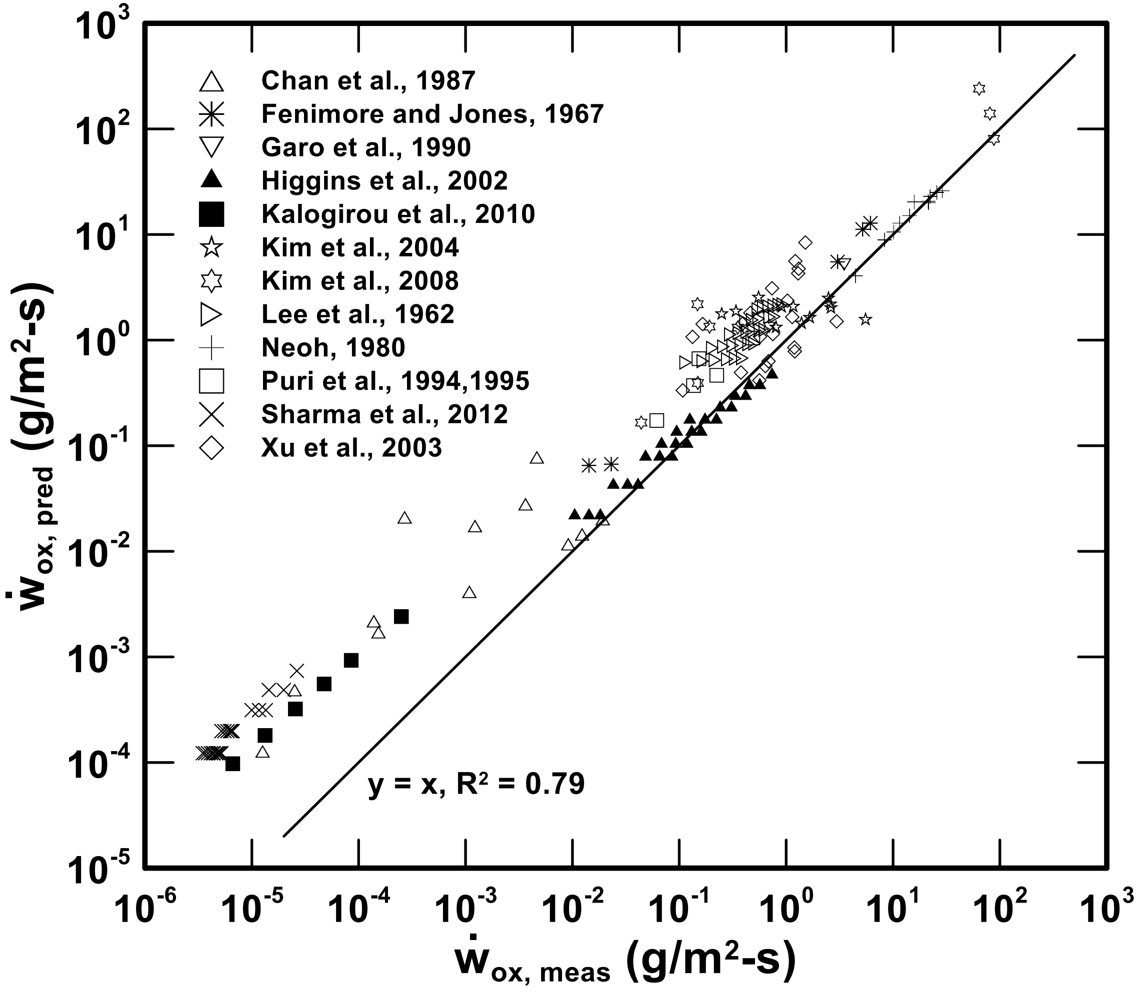
- For OH, Guo et al. (Fuel 2016) recommend:

$$\dot{w}_{ox,\mathrm{OH}} = (1.27 \times 10^{-3}\,\mathrm{K}^{0.5}\,\mathrm{s/m})\,p_{\mathrm{OH}}T^{-0.5}, \quad \text{i.e., } \eta_{\mathrm{OH}} = 0.10,$$

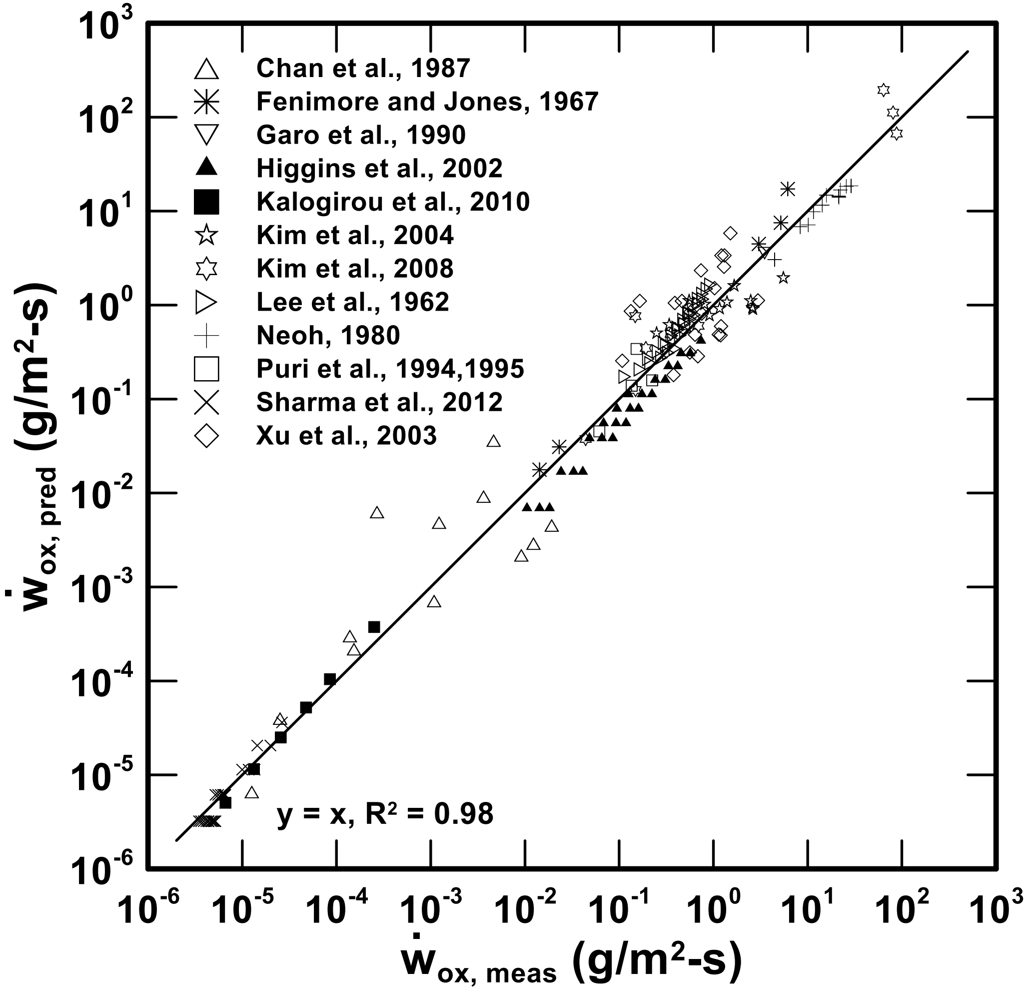
- The most widely used O_2 model is Nagle and Strickland-Constable (1962), but this generally overpredicts the rates. Instead, Guo et al. (Fuel 2016) recommend:

$$\dot{w}_{ox,\mathrm{O_2}} = (15.8\,\mathrm{K}^{0.5}\,\mathrm{s/m})\,p_{\mathrm{O2}}T^{-0.5}\exp\left(\frac{-195\,\mathrm{kJ/mol}}{R_u T}\right).$$

Soot oxidation rates

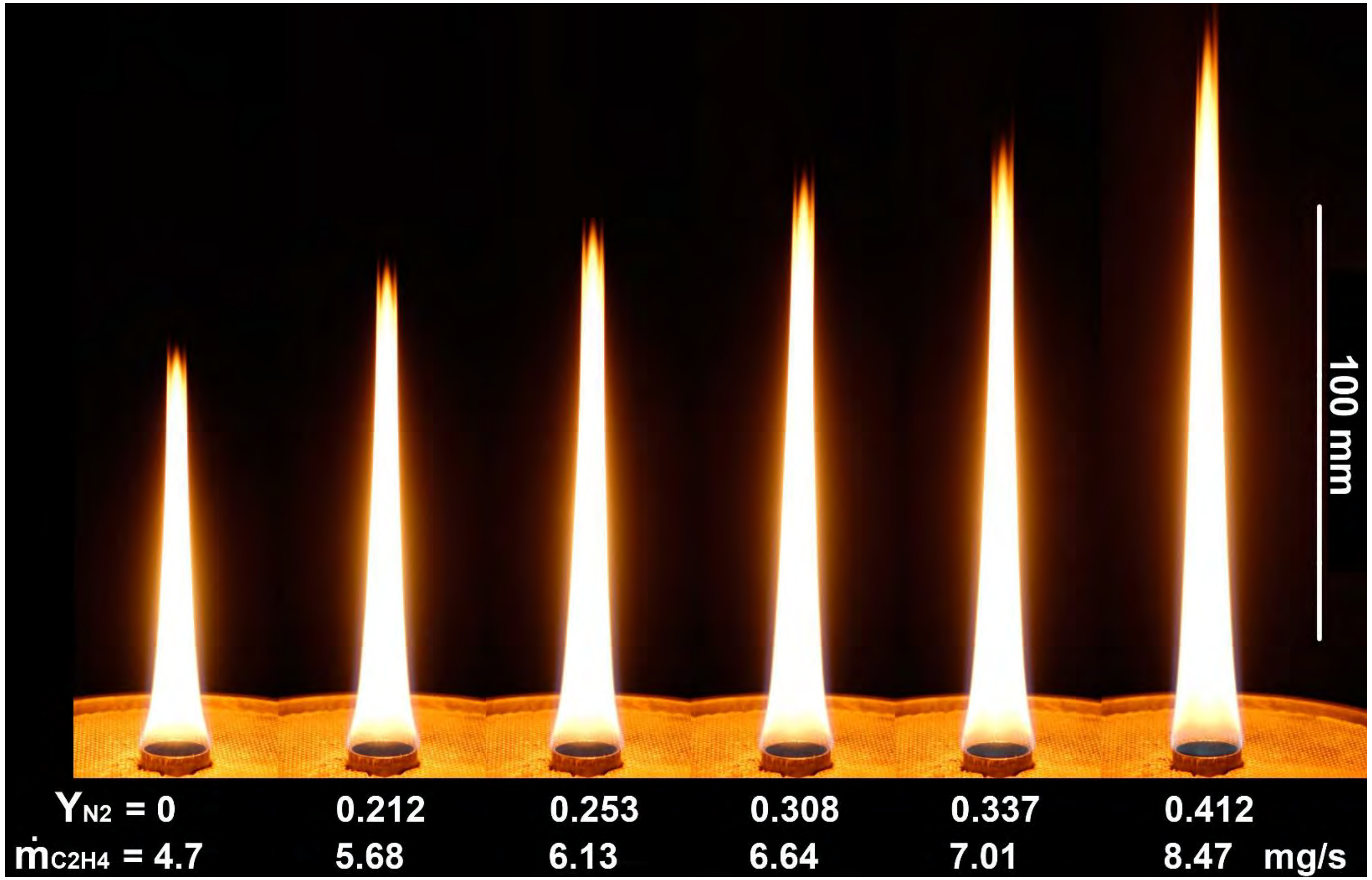


Neoh et al. for OH and NSC for O_2.



Guo et al. (Fuel 2016)

Laminar smoke points



Li and Sunderland (FSJ 2013)

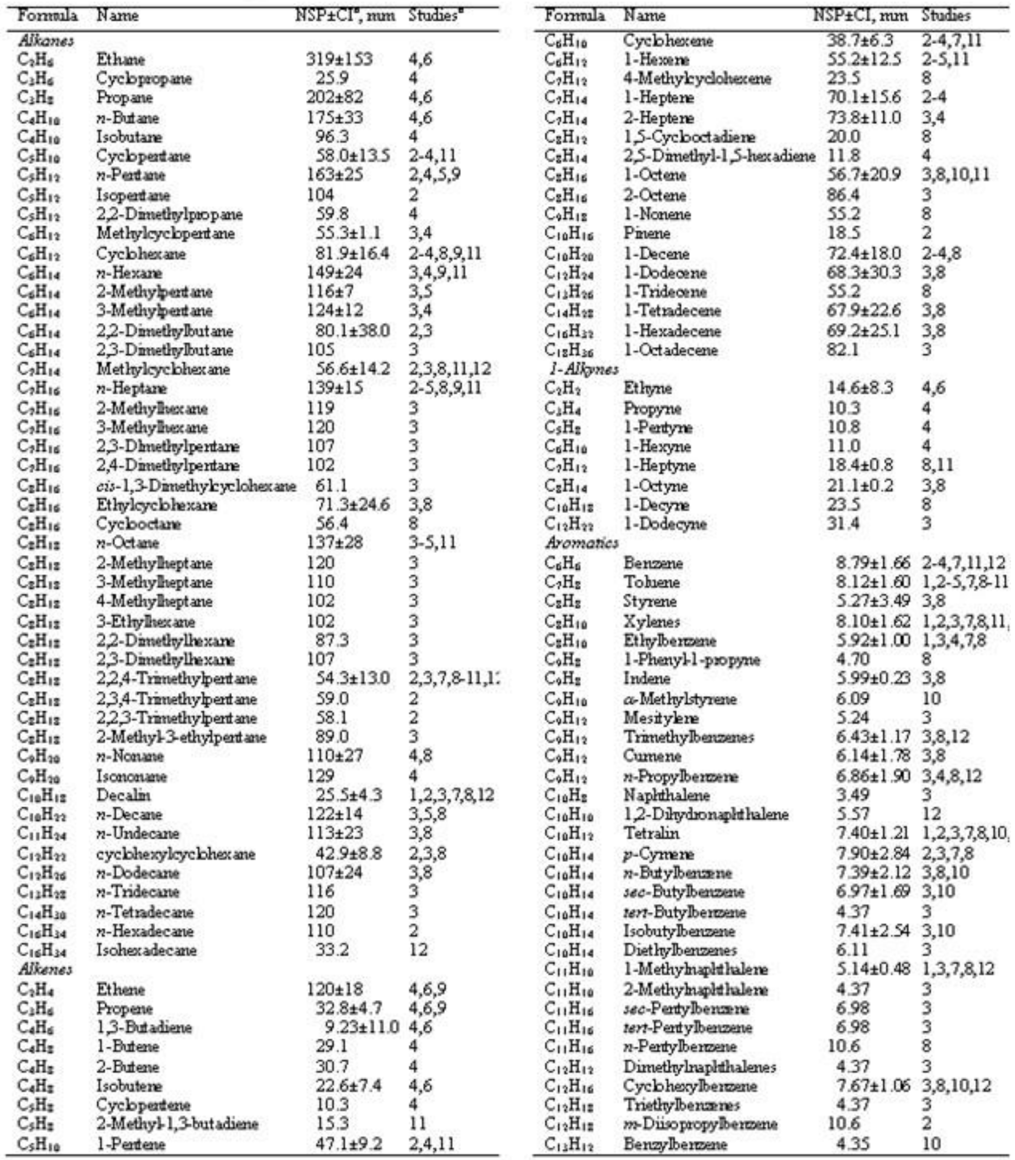
- A laminar smoke point is the condition and length of the incipient sooting of a diffusion flame.
- Smoke points are the prevailing measure of fuel sooting tendency in diffusion flames.
- Numerical fire models use smoke points, e.g., FDS, FireFOAM, Lautenberger et al. (FSJ 2005).

What causes smoke points?

There have been 3 leading explanations of smoke points:

1. Smoke points occur when T falls below 1300 K prior to soot burnout.
2. Smoke points occur when radiative loss fractions exceed 0.2 – 0.3.
3. Smoke points occur when t_{res} is long or when t_{form} / t_{oxid} is high.

Normalized smoke points



Formula	Name	NSP±CI[a], mm	Studies[a]
Alkanes			
C_2H_6	Ethane	319±153	4,6
C_3H_6	Cyclopropane	25.9	4
C_3H_8	Propane	202±82	4,6
C_4H_{10}	*n*-Butane	175±33	4,6
C_4H_{10}	Isobutane	96.3	4
C_5H_{10}	Cyclopentane	58.0±13.5	2-4,11
C_5H_{12}	*n*-Pentane	163±25	2,4,5,9
C_5H_{12}	Isopentane	104	2
C_5H_{12}	2,2-Dimethylpropane	59.8	4
C_6H_{12}	Methylcyclopentane	55.3±1.1	3,4
C_6H_{12}	Cyclohexane	81.9±16.4	2-4,8,9,11
C_6H_{14}	*n*-Hexane	149±24	3,4,9,11
C_6H_{14}	2-Methylpentane	116±7	3,5
C_6H_{14}	3-Methylpentane	124±12	3,4
C_6H_{14}	2,2-Dimethylbutane	80.1±38.0	2,3
C_6H_{14}	2,3-Dimethylbutane	105	3
C_7H_{14}	Methylcyclohexane	56.6±14.2	2,3,8,11,12
C_7H_{16}	*n*-Heptane	139±15	2-5,8,9,11
C_7H_{16}	2-Methylhexane	119	3
C_7H_{16}	3-Methylhexane	120	3
C_7H_{16}	2,3-Dimethylpentane	107	3
C_7H_{16}	2,4-Dimethylpentane	102	3
C_8H_{16}	*cis*-1,3-Dimethylcyclohexane	61.1	3
C_8H_{16}	Ethylcyclohexane	71.3±24.6	3,8
C_8H_{16}	Cyclooctane	56.4	8
C_8H_{18}	*n*-Octane	137±28	3-5,11
C_8H_{18}	2-Methylheptane	120	3
C_8H_{18}	3-Methylheptane	110	3
C_8H_{18}	4-Methylheptane	102	3
C_8H_{18}	3-Ethylhexane	102	3
C_8H_{18}	2,2-Dimethylhexane	87.3	3
C_8H_{18}	2,3-Dimethylhexane	107	3
C_8H_{18}	2,2,4-Trimethylpentane	54.3±13.0	2,3,7,8-11,1
C_8H_{18}	2,3,4-Trimethylpentane	59.0	2
C_8H_{18}	2,2,3-Trimethylpentane	58.1	2
C_8H_{18}	2-Methyl-3-ethylpentane	89.0	3
C_9H_{20}	*n*-Nonane	110±27	4,8
C_9H_{20}	Isononane	129	4
$C_{10}H_{18}$	Decalin	25.5±4.3	1,2,3,7,8,12
$C_{10}H_{22}$	*n*-Decane	122±14	3,5,8
$C_{11}H_{24}$	*n*-Undecane	113±23	3,8
$C_{12}H_{22}$	cyclohexylcyclohexane	42.9±8.8	2,3,8
$C_{12}H_{26}$	*n*-Dodecane	107±24	3,8
$C_{13}H_{28}$	*n*-Tridecane	116	3
$C_{14}H_{30}$	*n*-Tetradecane	120	3
$C_{16}H_{34}$	*n*-Hexadecane	110	2
$C_{16}H_{34}$	Isohexadecane	33.2	12
Alkenes			
C_2H_4	Ethene	120±18	4,6,9
C_3H_6	Propene	32.8±4.7	4,6,9
C_4H_6	1,3-Butadiene	9.23±11.0	4,6
C_4H_8	1-Butene	29.1	4
C_4H_8	2-Butene	30.7	4
C_4H_8	Isobutene	22.6±7.4	4,6
C_5H_8	Cyclopentene	10.3	4
C_5H_8	2-Methyl-1,3-butadiene	15.3	11
C_5H_{10}	1-Pentene	47.1±9.2	2,4,11
C_6H_{10}	Cyclohexene	38.7±6.3	2-4,7,11
C_6H_{12}	1-Hexene	55.2±12.5	2-5,11
C_7H_{12}	4-Methylcyclohexene	23.5	8
C_7H_{14}	1-Heptene	70.1±15.6	2-4
C_7H_{14}	2-Heptene	73.8±11.0	3,4
C_8H_{12}	1,5-Cyclooctadiene	20.0	8
C_8H_{14}	2,5-Dimethyl-1,5-hexadiene	11.8	4
C_8H_{16}	1-Octene	56.7±20.9	3,8,10,11
C_8H_{16}	2-Octene	86.4	3
C_9H_{18}	1-Nonene	55.2	8
$C_{10}H_{16}$	Pinene	18.5	2
$C_{10}H_{20}$	1-Decene	72.4±18.0	2-4,8
$C_{12}H_{24}$	1-Dodecene	68.3±30.3	3,8
$C_{13}H_{26}$	1-Tridecene	55.2	8
$C_{14}H_{28}$	1-Tetradecene	67.9±22.6	3,8
$C_{16}H_{32}$	1-Hexadecene	69.2±25.1	3,8
$C_{18}H_{36}$	1-Octadecene	82.1	3
1-Alkynes			
C_2H_2	Ethyne	14.6±8.3	4,6
C_3H_4	Propyne	10.3	4
C_5H_8	1-Pentyne	10.8	4
C_6H_{10}	1-Hexyne	11.0	4
C_7H_{12}	1-Heptyne	18.4±0.8	8,11
C_8H_{14}	1-Octyne	21.1±0.2	3,8
$C_{10}H_{18}$	1-Decyne	23.5	8
$C_{12}H_{22}$	1-Dodecyne	31.4	3
Aromatics			
C_6H_6	Benzene	8.79±1.66	2-4,7,11,12
C_7H_8	Toluene	8.12±1.60	1,2-5,7,8-11
C_8H_8	Styrene	5.27±3.49	3,8
C_8H_{10}	Xylenes	8.10±1.62	1,2,3,7,8,11,
C_8H_{10}	Ethylbenzene	5.92±1.00	1,3,4,7,8
C_9H_8	1-Phenyl-1-propyne	4.70	8
C_9H_8	Indene	5.99±0.23	3,8
C_9H_{10}	*α*-Methylstyrene	6.09	10
C_9H_{12}	Mesitylene	5.24	3
C_9H_{12}	Trimethylbenzenes	6.43±1.17	3,8,12
C_9H_{12}	Cumene	6.14±1.78	3,8
C_9H_{12}	*n*-Propylbenzene	6.86±1.90	3,4,8,12
$C_{10}H_8$	Naphthalene	3.49	3
$C_{10}H_{10}$	1,2-Dihydronaphthalene	5.57	12
$C_{10}H_{12}$	Tetralin	7.40±1.21	1,2,3,7,8,10,
$C_{10}H_{14}$	*p*-Cymene	7.90±2.84	2,3,7,8
$C_{10}H_{14}$	*n*-Butylbenzene	7.39±2.12	3,8,10
$C_{10}H_{14}$	*sec*-Butylbenzene	6.97±1.69	3,10
$C_{10}H_{14}$	*tert*-Butylbenzene	4.37	3
$C_{10}H_{14}$	Isobutylbenzene	7.41±2.54	3,10
$C_{10}H_{14}$	Diethylbenzenes	6.11	3
$C_{11}H_{10}$	1-Methylnaphthalene	5.14±0.48	1,3,7,8,12
$C_{11}H_{10}$	2-Methylnaphthalene	4.37	3
$C_{11}H_{16}$	*sec*-Pentylbenzene	6.98	3
$C_{11}H_{16}$	*tert*-Pentylbenzene	6.98	3
$C_{11}H_{16}$	*n*-Pentylbenzene	10.6	8
$C_{12}H_{12}$	Dimethylnaphthalenes	4.37	3
$C_{12}H_{16}$	Cyclohexylbenzene	7.67±1.06	3,8,10,12
$C_{12}H_{18}$	Triethylbenzenes	4.37	3
$C_{12}H_{18}$	*m*-Diisopropylbenzene	10.6	2
$C_{13}H_{12}$	Benzylbenzene	4.35	10

- Li and Sunderland (CST 2012) correlated the smoke points of 112 hydrocarbons from 12 studies.

Soot diagnostics

- Particle sizes via transmission electron microscopy (TEM), light scattering, or mass spectrometry.
- Soot temperatures via pyrometry.
- Soot concentrations via laser extinction, soot optical emissions, or laser-induced incandescence (LII).

Soot as temperature sensor

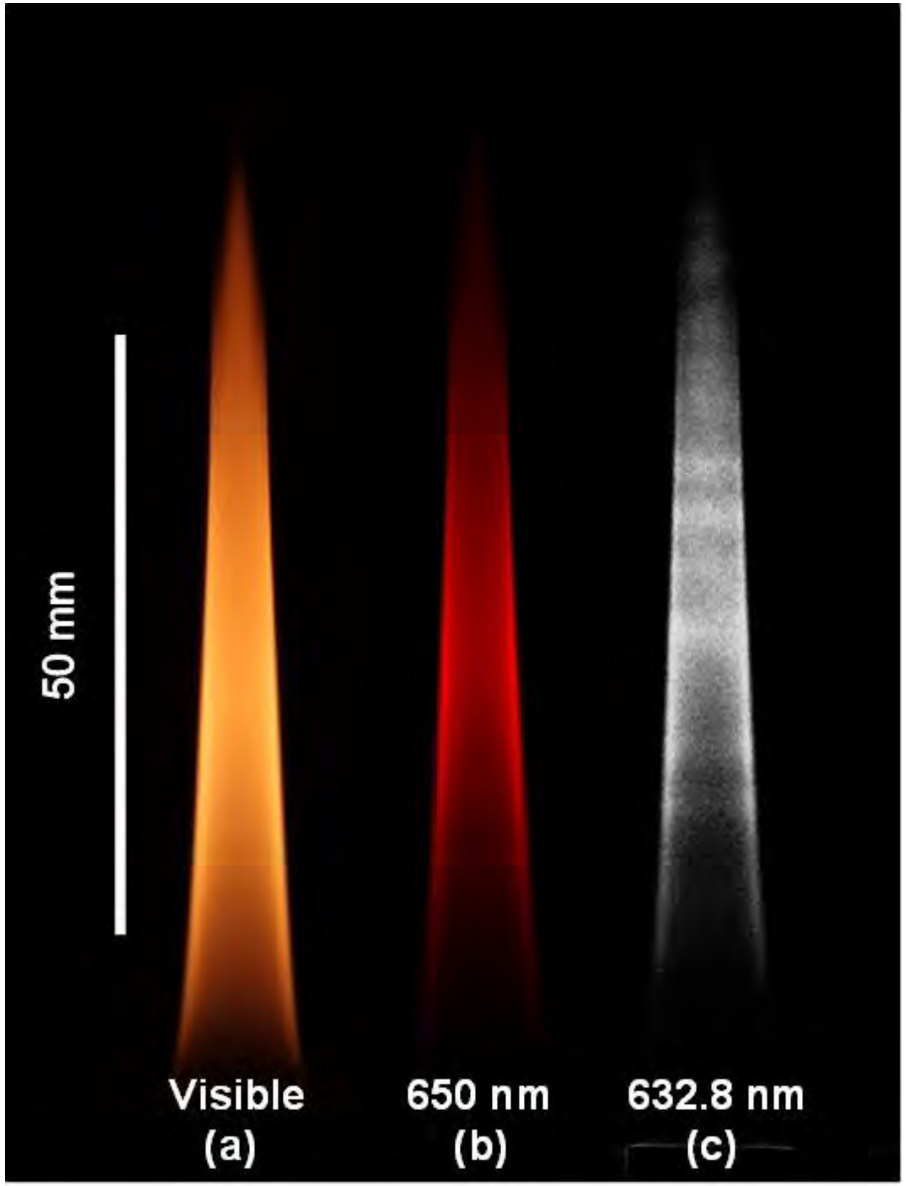
- Thermocouples are available as small as 25 µm.
- Soot particles have diameters of about 30 nm.
- Radiative losses in probes scale according to:

$$T_{gas} - T_{probe} = d\, Nu\, \sigma\, \varepsilon\, T_{probe}^{4} / k$$

The thermal accommodation coefficient is a measure of non-continuum heat transfer effects. For soot it is nearly unity.

C_2H_4 flame

- Fuel: ethylene
- Oxidizer: coflowing air.
- Flame height: 88 mm
  - ☐Steady
  - ☐Optically thin
  - ☐Axisymmetric



Guo et al., AO 2013

Abel transform

- Based on an exact solution
- Requires discretization

Line-of-sight integration of the flame property *f*(*r*) is:

$$p(x) = \int_{-\infty}^{\infty} f(r)\,dy$$

Substituting *y* with *x* and *r* following $r^2 = x^2 + y^2$ yields:

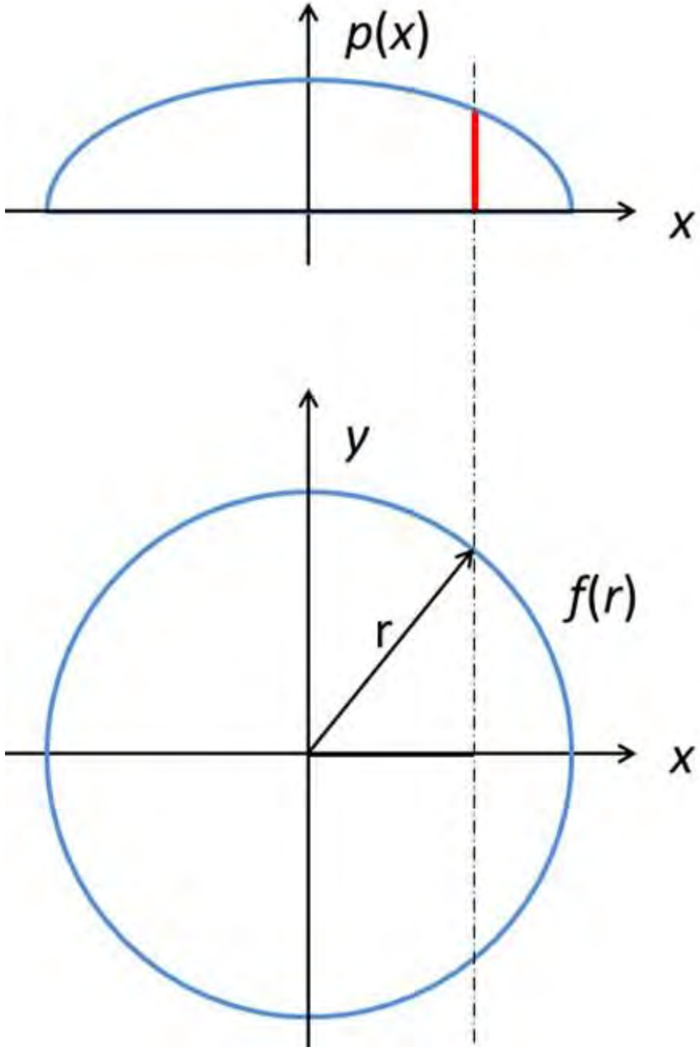
$$p(x) = 2\int_{x}^{\infty} \frac{r f(r)}{\sqrt{r^2 - x^2}}\,dr$$

Analytical inverse of the above equation yields:

$$f(r) = -\frac{1}{\pi}\int_{r}^{\infty} \frac{p'(x)}{\sqrt{x^2 - r^2}}\,dx$$

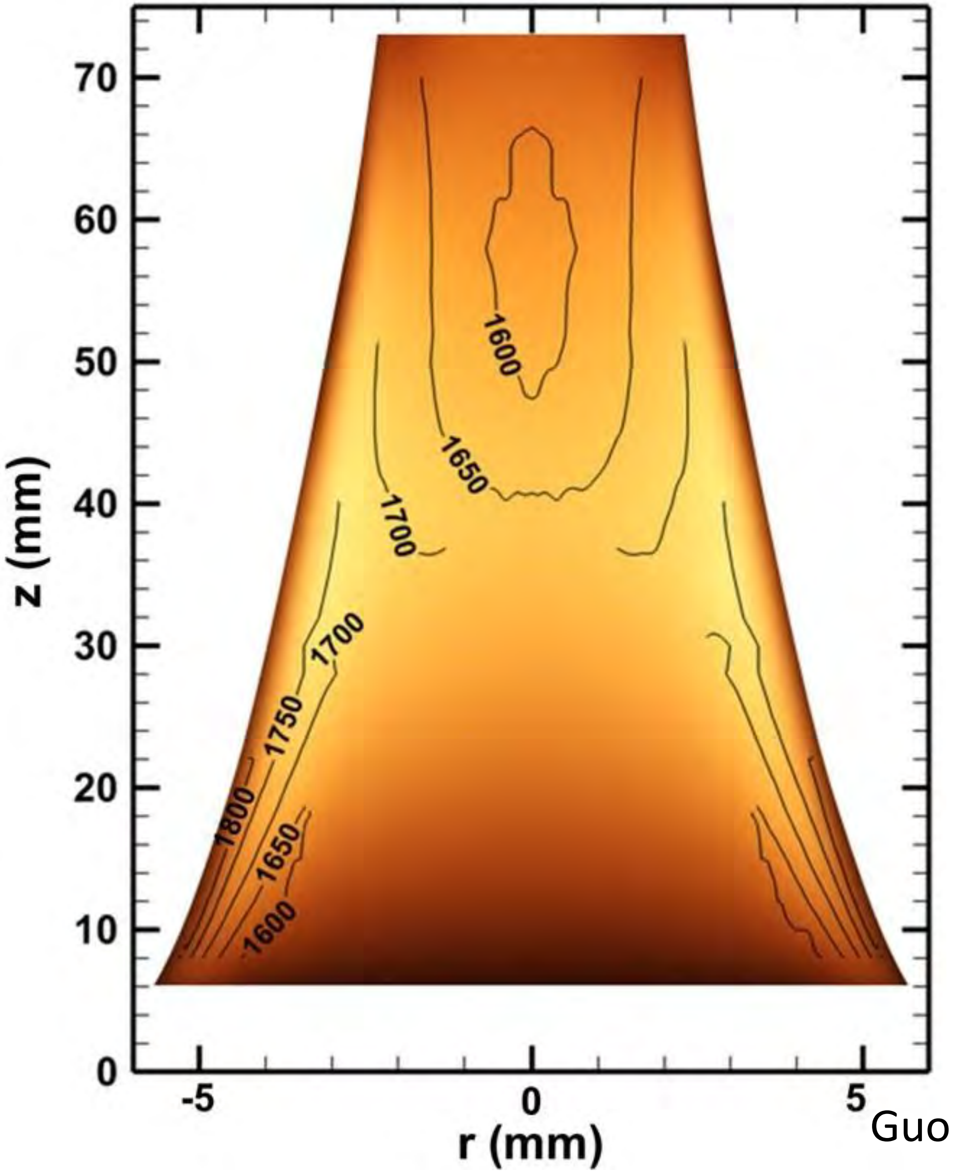
Sensitive to noise

Singularity at $x = r$



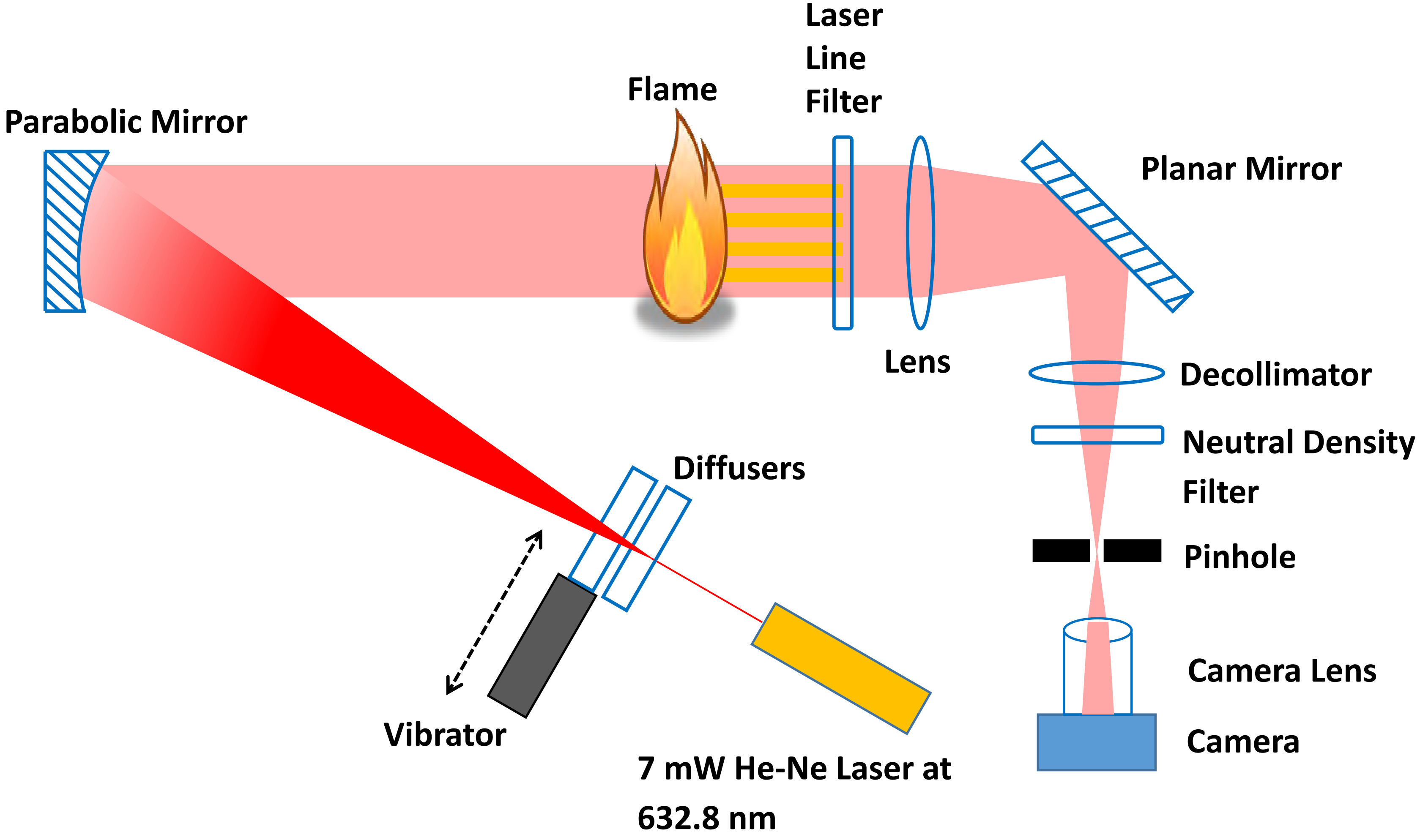
Soot pyrometry contours

- T range: 1600 – 1850 K.
- Spatial resolution: 23 µm
- Shutter time: 125 ms
- Uncertainty: ± 50 K
- Precision: ± 0.1 K



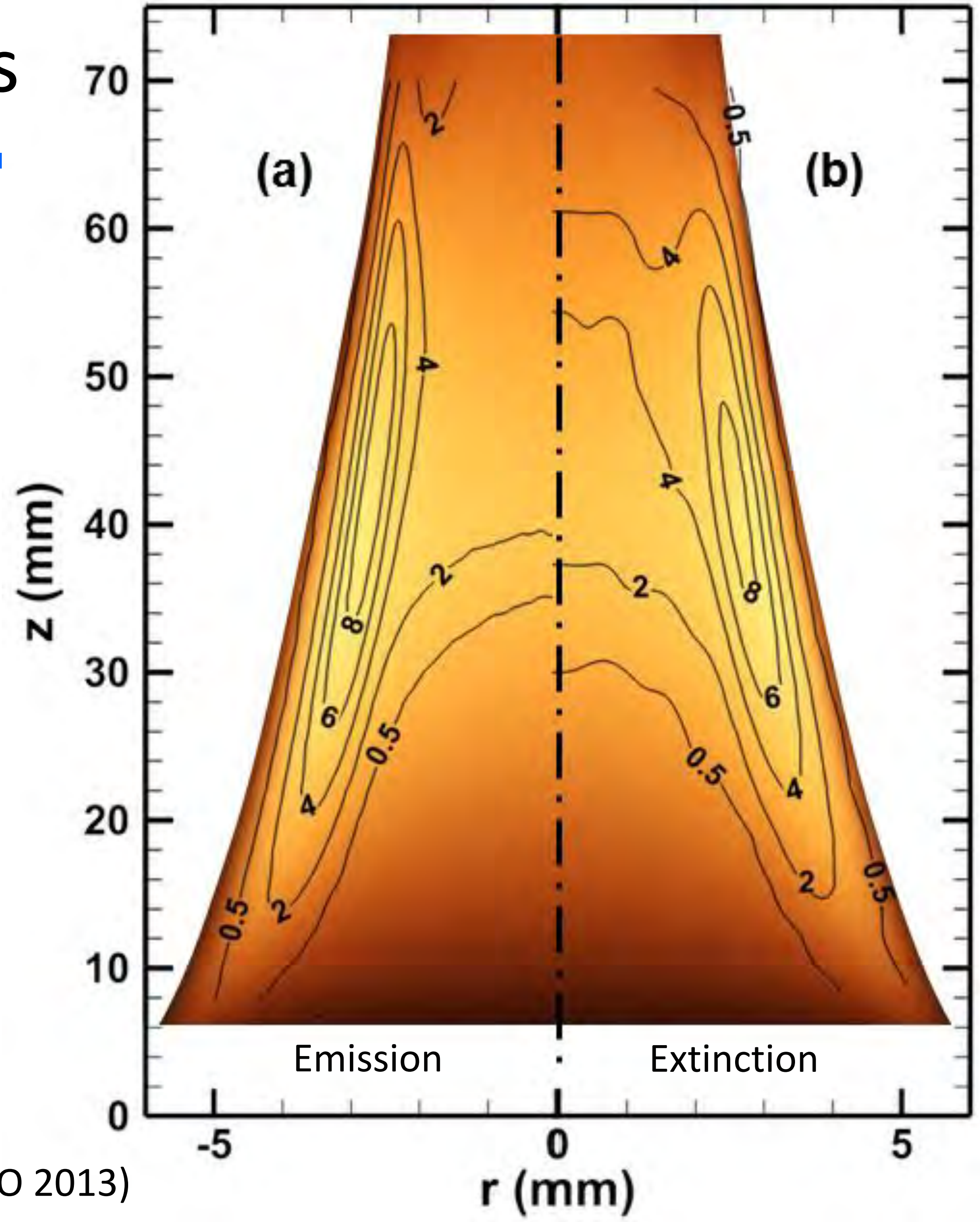
Guo et al. (AO 2013)

Laser extinction by soot



Soot volume fractions

	Emission	Extinction
f_s (ppm)	0.1-10	0.2-10
Res. (µm)	23	34
t (ms)	125	167
Precision (ppm)	$\pm 4\times10^{-4}$	$\pm 6\times10^{-4}$
Uncertainty	± 30%	± 10%



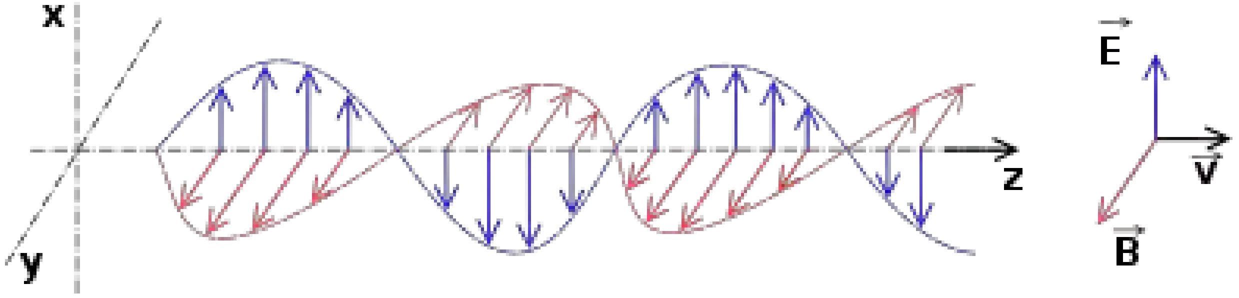
Guo et al. (AO 2013)

Thermal Radiation

- Radiation in fires is heat transfer via electromagnetic waves (EMR).

- All materials emit and absorb EMR.

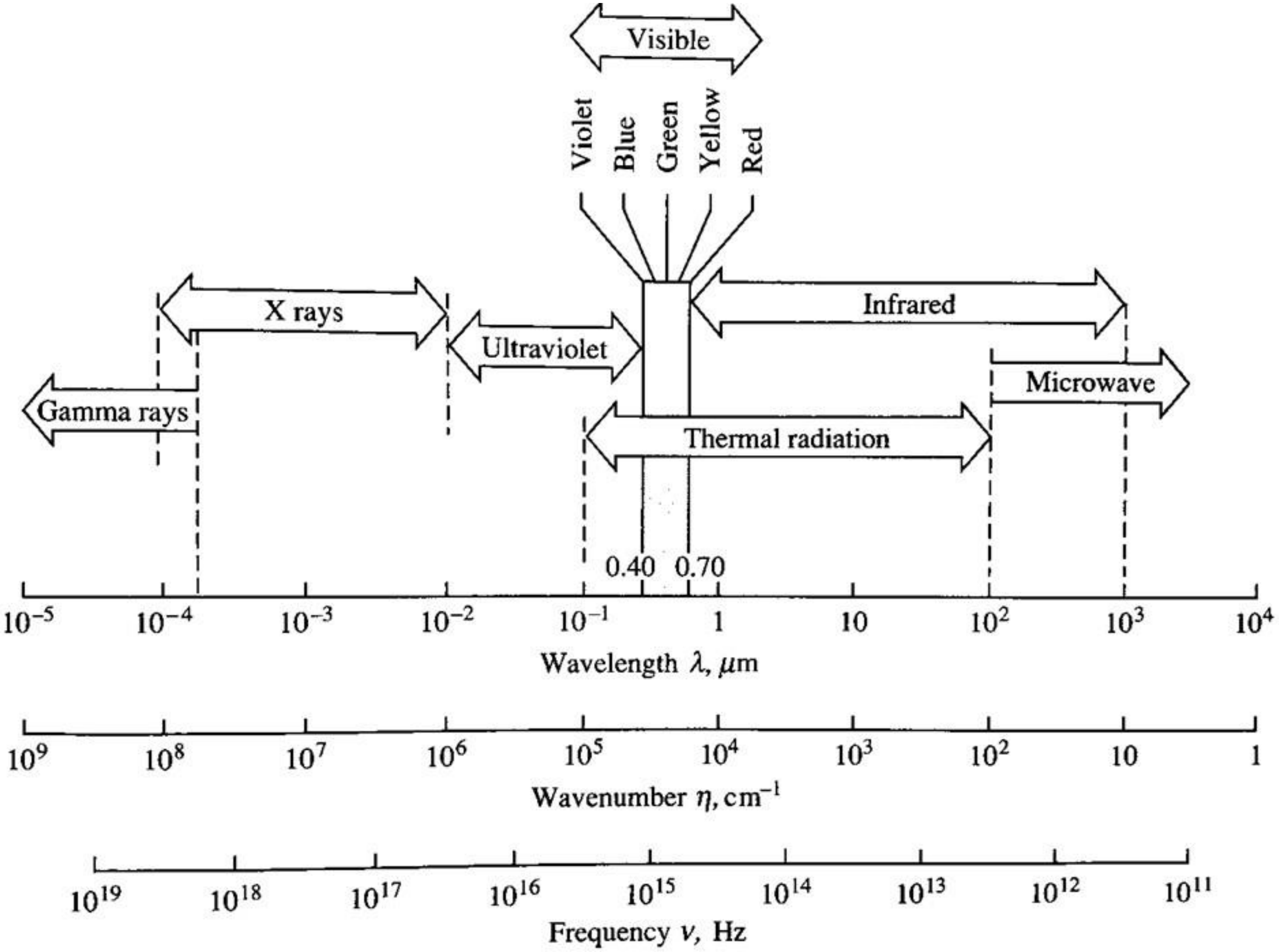
- Unlike conduction and convection:
  - Radiation can span long distances
  - Radiation scales with T^4
  - Radiation requires no medium
  - Radiative properties of materials are very complex



wikipedia

- Radiation is a key factor in wildland fire spread (Rossi et al. FSJ 2011; Finney et al. PNAS 2015; Balbi et al. IJWF 2020).

EMR spectrum



$\lambda = 1 / \eta$

wavelength = 1 / wavenumber

Modest (1993)

Radiation from surfaces

Planck's Law gives the blackbody spectral emissive power:

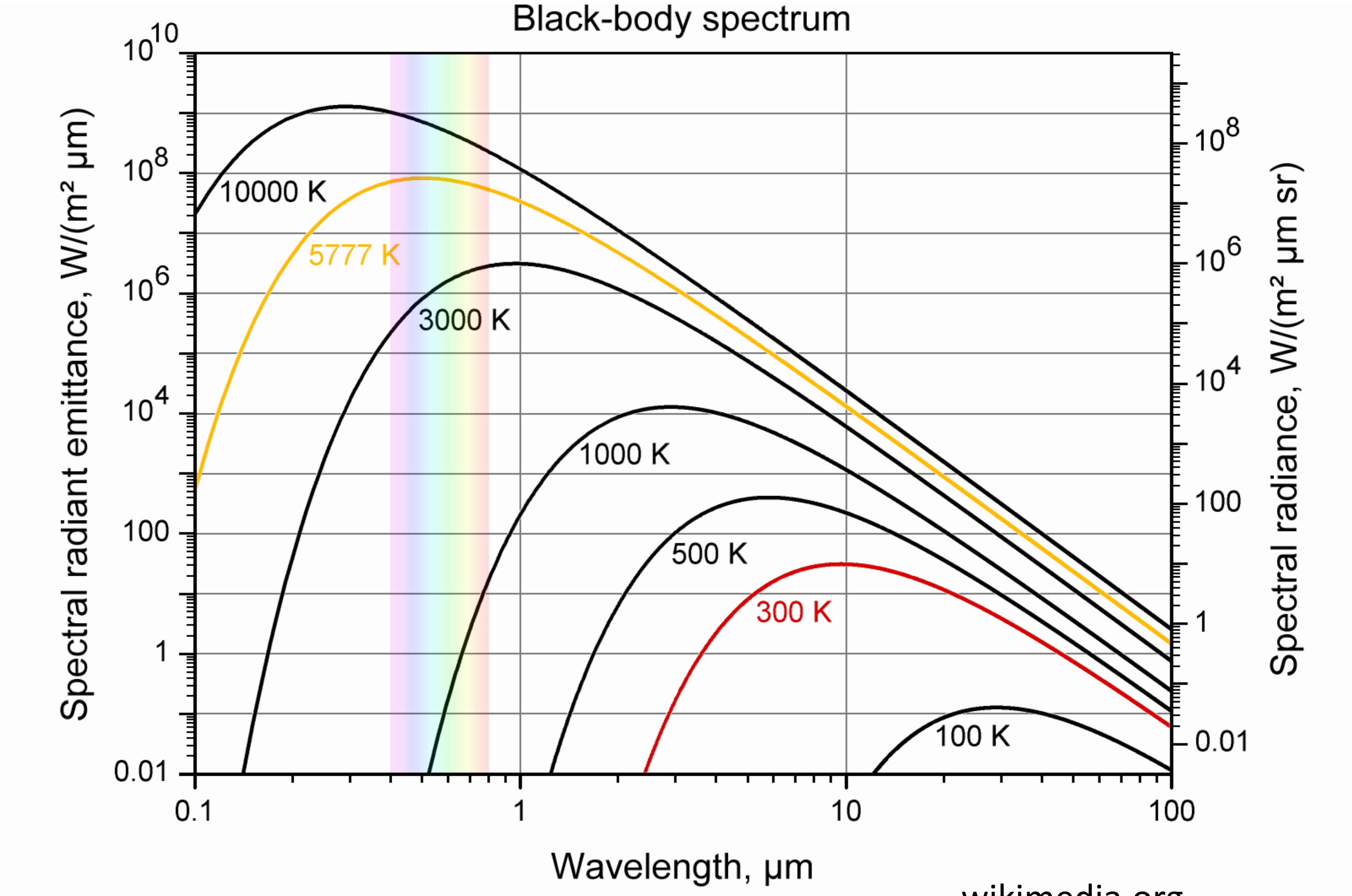
$$E_{b\lambda} = \frac{C_1}{\lambda^5\,[\exp\left(\frac{C_2}{\lambda T}\right) - 1\,]}$$

Integrating yields the total emissive power (the Stephan-Boltzmann Law):

$E = \sigma T^4$

Wein displacement law:

$\lambda_{max} = b / T$



wikimedia.org

IR spot detectors

- Measure radiation (heat flux) from surfaces.
  - As temperature increases, radiation increases
- Range up to ~3,300 K,
- Must account for surface emissivity, reflection, ash, and smoke.

IR imagers

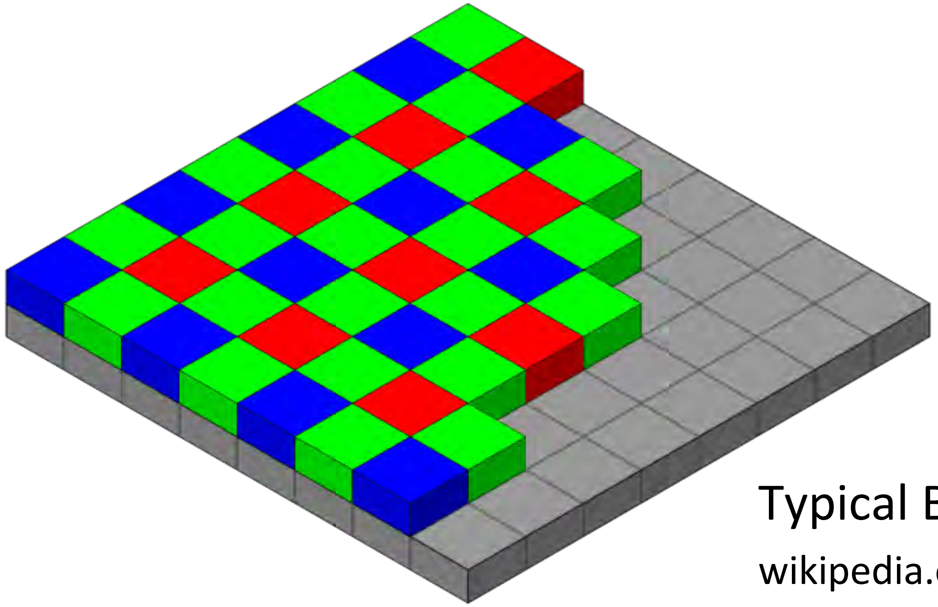
- There are two types of IR imagers:
- Thermal detectors: limited pixel counts (1.2 MP), cost up to $20k.
- Quantum detectors: fast and sensitive, but most require cryogenic cooling, cost up to $150k.
- IR lenses are costly, often made of calcium fluoride, sapphire, or germanium.
- IR imagers are common for satellite fire observations (Terra, Aqua, MODIS, EROS, GOES, VIIRS, etc.), with ~1 km resolution.
- From 5 µm – 8 µm there is atmospheric attenuation from H_2O and CO_2.

Omega TIC, $1,000

FLIR x6800sc
0.33 MP, $100k

Color cameras

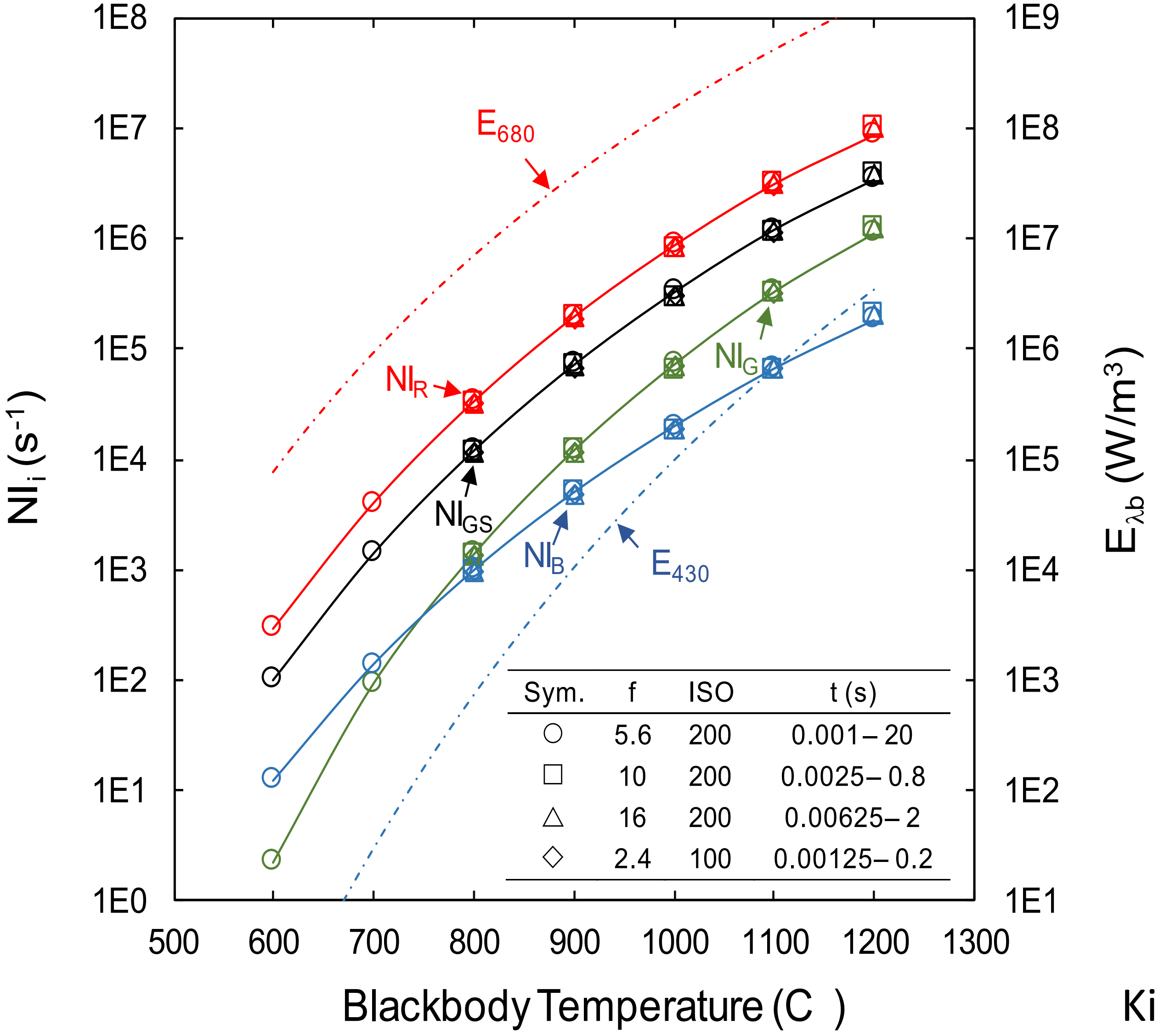
- Sony DSC-RX10 III, $1,300
- 14 bit CMOS sensor, 20.1 MP
- Negligible dark current
- *FL* = 24 mm and *f* = 2.4



Typical Bayer filter array.

wikipedia.org

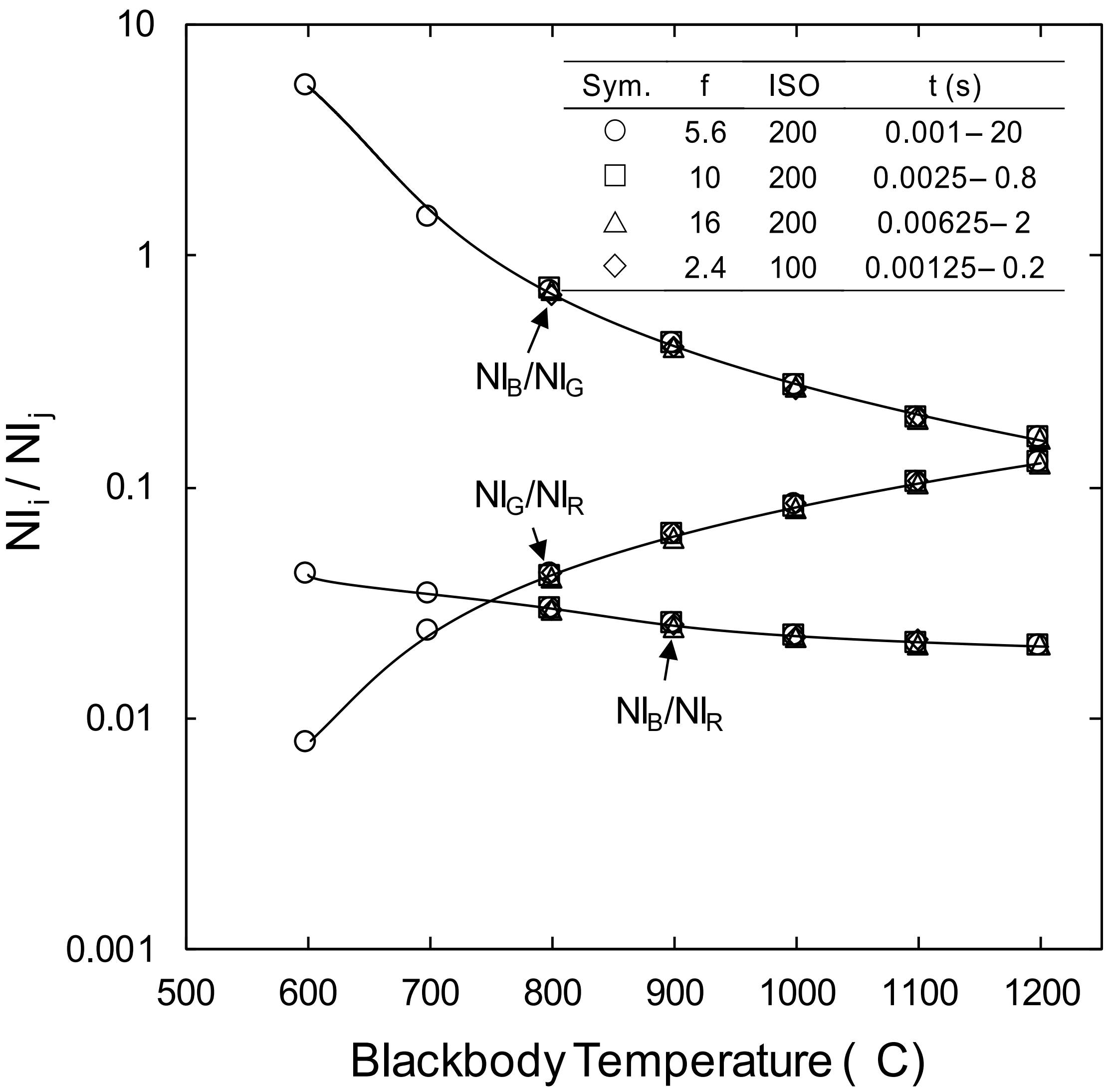
Single-band pyrometry



Sym.	f	ISO	t (s)
○	5.6	200	0.001– 20
□	10	200	0.0025– 0.8
△	16	200	0.00625– 2
◇	2.4	100	0.00125– 0.2

Kim and Sunderland (FSJ 2019)

Ratio pyrometry



Kim and Sunderland (FSJ 2019)

Single-band vs. ratio pyrometry for fires

	Single-Band Pyrometry	**Ratio Pyrometry**
Key Assumptions	• $\varepsilon\ \tau$ is a required input • Fire dwell time and image size must be known	• $\varepsilon\tau$ is the same at both wavelengths
Key Advantages	• SNR is 18 times that of ratio pyrometry	• No assumption of $\varepsilon\tau$ is required • Neither fire dwell time nor image size must be known

Combine these to obtain the flame radiative flux at every pixel.

Radiative emissions from color pyrometry

The spectral emissive power from an ember and passing through smoke is:

$$E_\lambda = \frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T_{sb}}\right)-1\right]}\,.$$

It can also be found from:

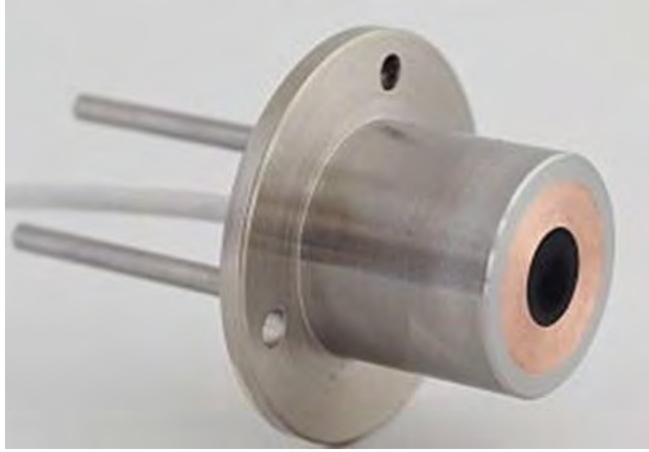
$$E_\lambda = \frac{C_1\,\varepsilon\,\tau}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T_{ratio}}\right)-1\right]}\,.$$

Combining yields emissivity times transmittance:

$$\varepsilon\,\tau = \exp\left[-\frac{C_2}{\lambda}\left(\frac{1}{T_{sb}}-\frac{1}{T_{ratio}}\right)\right].$$

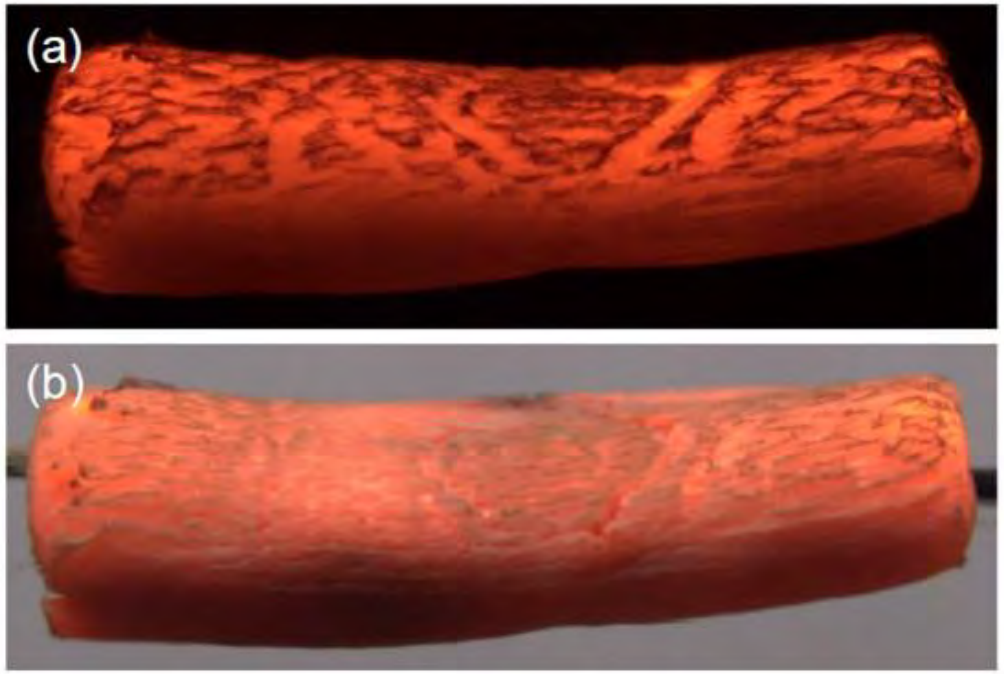
The heat flux is:

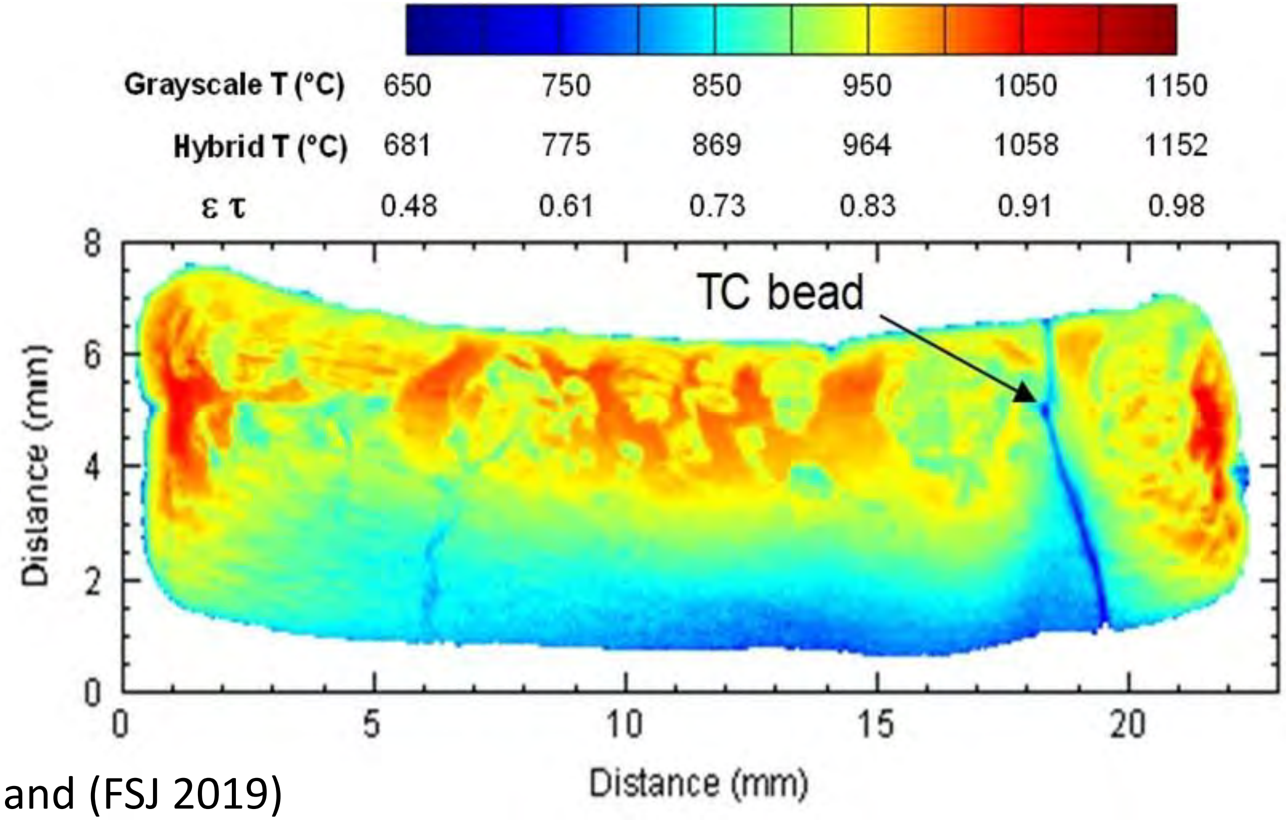
$$\dot{q}'' = \varepsilon\,\tau\,\sigma\,T_{ratio}^4$$



Medtherm

Ember pyrometry with color camera

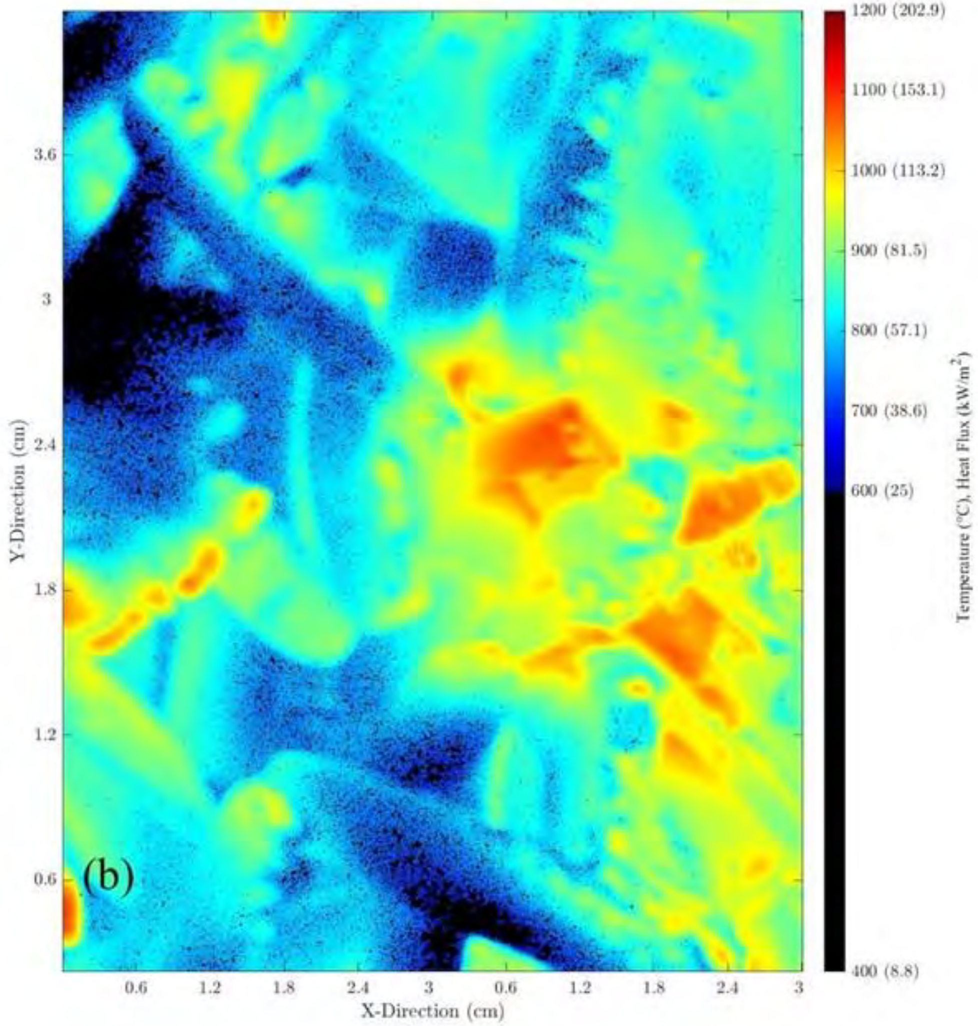




Kim and Sunderland (FSJ 2019)

Heat fluxes of ember piles

Color image of ember pile



Temperature and heat flux

Tlemsani et al. (2023)

Thin-filament pyrometry

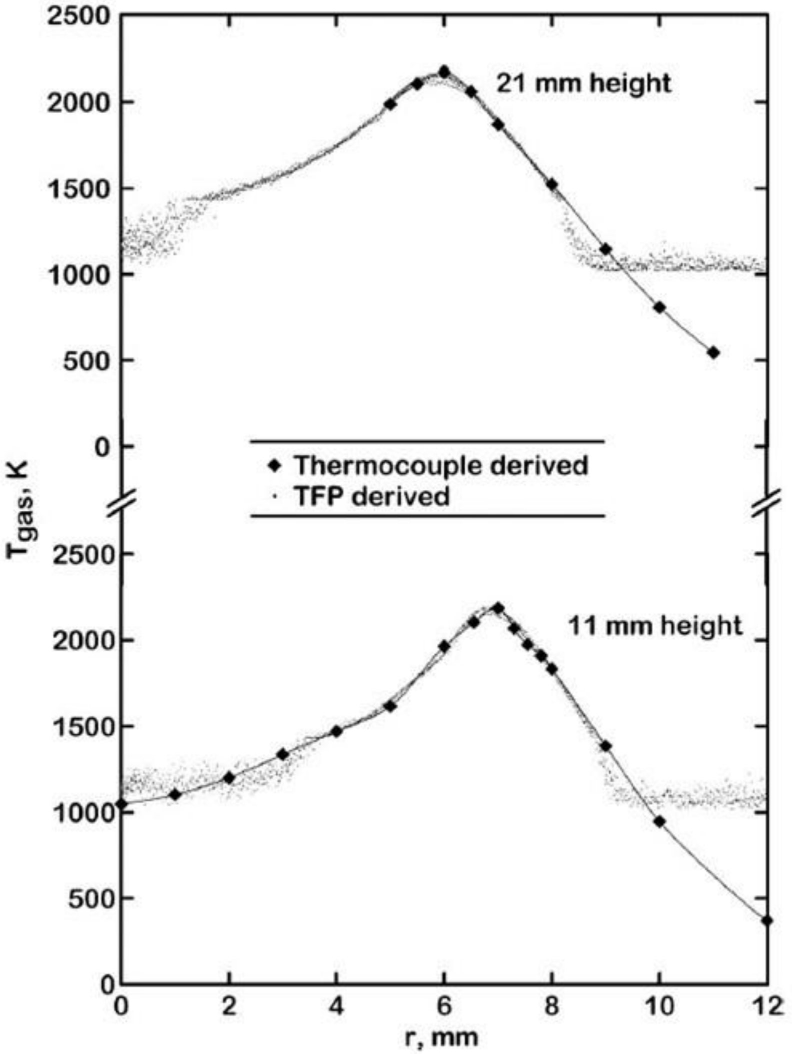
- SiC fibers, 15 µm diameter
- Filament emissivity: 0.88
- Radiation correction is required:

$$h\,(T_{gas} - T_{fiber}) = \sigma\,\varepsilon\,(T_{fiber}^{4} - T_{\infty}^{4})$$

$$Nu = h\,d_{fiber} / k_{gas}$$

$$Pe = u\,d_{fiber} / \alpha_{gas}$$

$$Nu = [\,0.8237 - 0.5\,\ln(\mathrm{Pe})\,]^{-1}$$



Maun et al. (AO 2007)

Radiation in absorbing, emitting, and scattering media

Every point in space can interact with every other point – at the speed of light.
Every wavelength, species, and temperature can behave differently.

Many radiative transport equations (RTEs) are integro-differential equations, e.g.:

$$\begin{aligned}
\mu \frac{dL_\nu}{d\delta_\nu} = {} & L_\nu(\delta_\nu, \mu, \phi) - (1-\kappa_\nu) \int_0^{2\pi} d\phi' \int_{-1}^{+1} L_\nu(\delta_\nu, \mu', \phi') \{ p_\nu(\delta_\nu, \mu, \phi, \mu', \phi')/4\pi \} \, d\mu' \\
& - (1-\kappa_\nu) E_\nu^0 \exp\left(-\frac{\delta_\nu}{\mu_0}\right) \{ p_\nu(\delta_\nu, \theta, \phi, \theta^0, \phi^0)/4\pi \} \\
& - \kappa_\nu B_\nu(\delta_\nu).
\end{aligned}$$

Schwarzchild equation

In an absorbing gas or aerosol, radiative intensity decreases with distance as:

$$\mathrm{d}I / \mathrm{d}x = -\kappa I \,,$$

where κ = absorption coefficient, aka attenuation coefficient or extinction coefficient.

This is the simplest RTE

Integrate, assuming constant κ, to obtain the Lambert-Beer-Bouger Law,

$$\frac{I}{I_0} = e^{-\kappa L} \equiv \tau \,,$$

where τ is transmittance, aka transmissivity.

The path absorptivity is found from: $\alpha + \tau = 1$

Schwarzchild and Lambert-Beer-Bouger are often written in spectral form.

Optical depth

Optical depth, aka optical thickness, is

$$\tau \equiv \kappa L ,$$

and is dimensionless.

$$0 \leq \tau \leq \infty$$

$\tau << 1$ ←→ optically thin

$\tau >> 1$ ←→ optically thick

Radiation from flames

The spectral radiative power from a flame is:

$E_\lambda = \varepsilon_\lambda \frac{C_1}{\lambda^5\,[\exp\left(\frac{C_2}{\lambda T}\right)-1\,]}$, where

$\varepsilon_\lambda = 1 - e^{-\kappa_\lambda L}$

An integration over all λ yields

$E = \Sigma\, \varepsilon_i\, \sigma T^4$, with

$\varepsilon_i = 1 - e^{-\kappa_p\, p\, L}$,

where the summation is over all the species, κ_p is the Planck mean absorption coefficient, *p* is partial pressure.

There are three type of flame absorption/radiation models:

1. Line-by-line spectral models, e.g., statistical narrow band (SNB).
2. Band spectral models, e.g., wide-band models (WB).
3. Global models, e.g., weighted sum of gray gas (WSGG).

A reasonable approximation is the global radiant fraction model (Ahmed 2023), where χ_r = 15% (alcohols) to 50% (aromatics).

Aerosol scattering

An aerosol is a mixture of gas and small liquid or solid particles.

Aerosols can interact with light in unusual ways.

Particle regime	Particle diameter	Scattering model	Model complexity
Small	$< 0.1\,\lambda$	Rayleigh	Simple
Medium		Mie	Complex
Large	$> \lambda$	Geometric optics (ray tracing)	Simple

Soot extinction

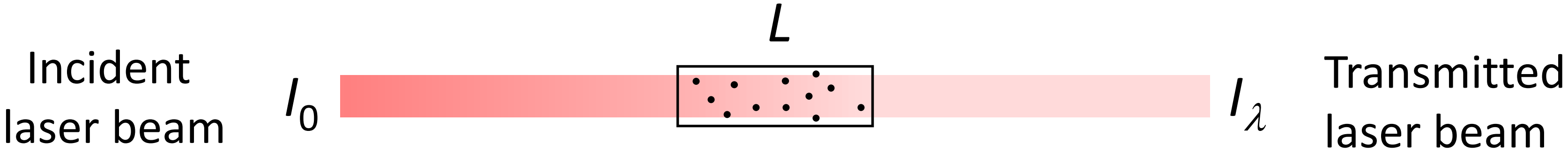
- Rayleigh scattering for soot yields

$$\kappa_\lambda = 6\,\pi\,E(m)\,f_s\,/\,\lambda\,,$$

with refractive index absorption function $E(m) = 0.26$ for soot with a refractive index of $m = 1.57 – 0.56\,i$

Note that soot emissivity also scales with $1\,/\,\lambda$.

- From Lambert-Beer-Bouger Law: $\frac{I_\lambda}{I_0} = e^{-\kappa_\lambda L}$



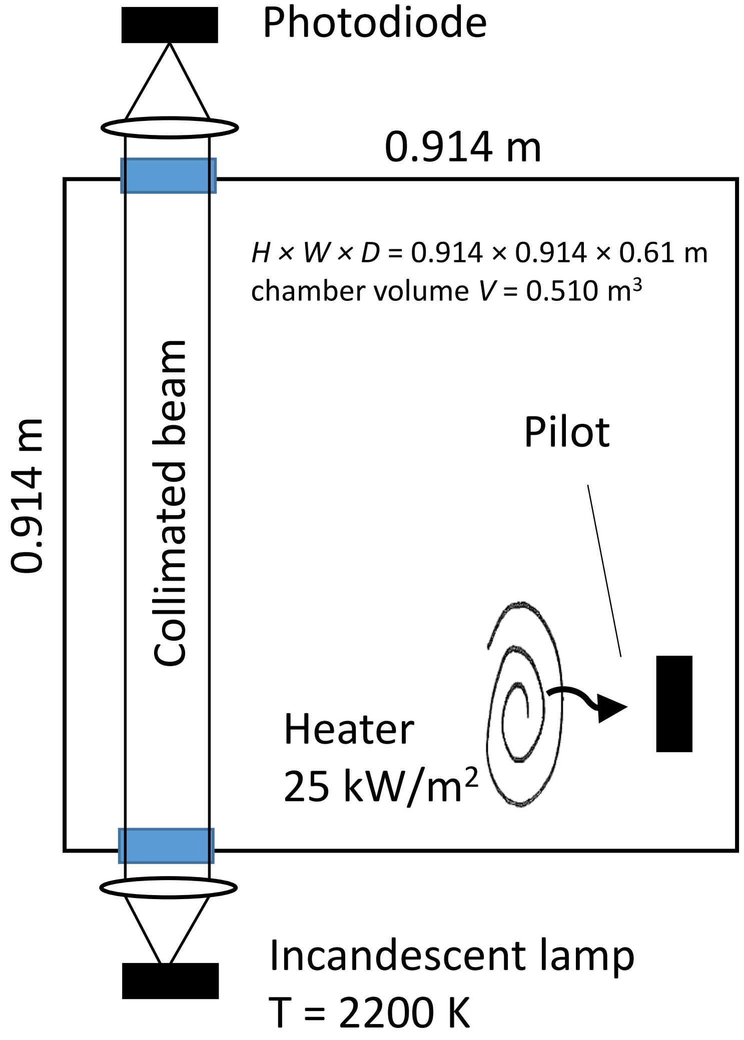
ASTM E662 smoke chamber

Also NFPA 258, IEC 60695-6-30

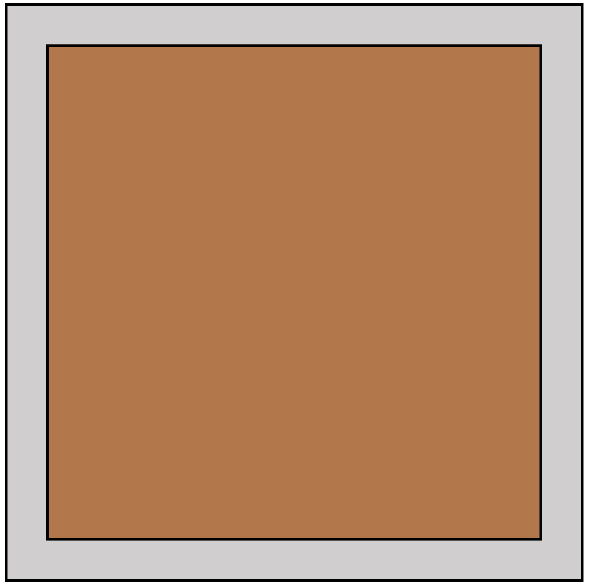
ASTM E662 features:

A sealed chamber
Only one surface exposed
A vertical light beam
Quantitative measures, namely
D_m, D_{mass}, and *SOI*.

Smoke chamber



$H \times W \times D$ = 0.914 × 0.914 × 0.61 m
chamber volume V = 0.510 m^3



Specimen size: 76.2 × 76.2 mm
Open area: 65.1 × 65.1 mm
Al foil on back, sides, and top edge
Thickness $\leq$ 25 mm

Summary

- Soot is formed only in flaming combustion, but other solid aerosols are often called soot.
- The complexity of soot is infinite, but the best simple models have changed little since 2000.
- The small size of soot makes it ideal for pyrometry.

- Radiative emissions from fires vary from 15 – 50%.
- Radiation can dominate wildland fire spread rates.
- Accurate measurements and simulations of fire radiative behavior are challenging.

Craighill bonfire
https://twitter.com/EmmaVardyTV/status/1414393963075837956