

Burgers Program and Combustion Institute Summer School on Fire Safety Science –

Wildland/WUI Fire Behavior, June 6, 2023



Soot and Radiation



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Acknowledgments: K. Allan, P. Anderson, J. Castillo, H. Guo, V. Lecoustre, L. Li, J. Maun, NASA, NIST, NSF



What is soot?



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

FIRE

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

Description of Sold Wile Your Your Woman

SATURDAY APRIL 21, 2001



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

By ANDREW C. REVKIN

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NATURE VOL 409 PFEBRUARY 2001 www.mature.com

news and views

The dark side of aerosols

Melenat O. Anciese

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

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Strong radiative heating due to the mixing state of black carboa in atmospheric aerosals

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Annuals affect the farth's temp-minery and climate by aftering the vallative properties of the attoschere. A large positive compleneps of this radiation furthing from according to bin hinds carbon-asso-that is released from the burning of front fuel and harmon, and, as a lesser extent, mattern tires, but the energy fording is affected by how black cathies is mixed with allow arrived monitorion. Trum analia of across rediative facting, it is known that black cathent caracter to one ill serviced possible mining states: distinct from other armoul particles instermily mitted" 'I we terrineposited withits doesn (incommally notare" "), we be black-current inversability a well mixed theil". But so he if her been assumed that accouls other protomizzetly as an external minuters, Here I standate the evolution of the chamical compositions of accords, firsting that the mining state and direct fielding of the black on-how component approach these of an internal evictore, lergely due to computation and prooth of armavit particles. This finding implies a higher positive limiting from black carfae that perstantly thought, suggesting that the muturing effect from black control may many balance the net couling effect. of other authorsessaril: nerosofi transitizants. The anapalaude of the largest radiative foresting from black exclose uself a monde that due to City, suggesting that black afters may be the second read important composition of globall regaring after 'O, in terms of direct intelim.

Soot in fires





FIRE

- 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.

Hickory Record, 2013



Soot benefits and hazards



Benefits Radiation in boilers Rubber additive Printer toner Pigments Lubrication Filtration Candles

Hazards 60,000 US deaths annually Cytotoxic, carcinogenic CO emission Climate change **Fire spread** Fire obscuration 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



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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)





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

$$J_{Moss} = 6 \times 10^{6} \bar{\rho}^{2} N_{A} \sqrt{T} \exp\left(\frac{-46100}{T}\right) X_{C_{2}H_{2}}$$
$$J_{Leung} = \frac{2}{C_{m}} N_{A} 1.7 \exp\left(\frac{-7548}{T}\right) C_{C_{2}H_{2}}$$
$$J_{Fairweather} = \frac{2.7 \times 10^{6}}{\rho_{s} C_{m}} N_{A} \exp\left(\frac{-46100}{RT}\right) C_{C_{2}H_{2}}$$

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):

$$\omega_{\rm g} = k_{\rm g}(T) [C_2 H_2] \sqrt{\pi \left(\frac{6M_C}{\pi \rho_C}\right)^{2/3}} [C]^{1/3} (\rho N)^{1/6}$$

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

```
C_{\text{soot}} - H + H \rightarrow C_{\text{soot}} + H_2C_{\text{soot}} + H \rightarrow C_{\text{soot}} - H
```

```
C_{\text{soot}} \cdot + C_2 H_2 \rightarrow C_{\text{soot}} \text{-} 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 O₂, with smaller contributions from O, H₂O, and CO₂:

 C_{soot} + OH → CO + products C_{soot} + O_2 → 2 CO + products

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

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

 The most widely used O₂ model is Nagle and Strickland-Constable (1962), but this generally overpredicts the rates. Instead, Guo et al. (Fuel 2016) recommend:

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



10³

10²

10¹

10⁻³

10⁻⁴

10⁻⁵

10⁻⁶

10⁻⁵

Δ

 \Diamond

Chan et al., 1987

Garo et al., 1990

Kim et al., 2004

Kim et al., 2008

Lee et al., 1962

Xu et al., 2003

10⁻⁴

Neoh, 1980

Higgins et al., 2002

Kalogirou et al., 2010

Puri et al., 1994,1995

Δ

 $y = x, R^2 = 0.79$

10⁻³

Sharma et al., 2012

Fenimore and Jones, 1967

Soot oxidation rates

10²

10³



Neoh et al. for OH and NSC for O_2 .

10⁻²

w_{ox, meas} (g/m²-s)

10⁻¹

10[°]

10¹

Guo et al. (Fuel 2016)

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Laminar smoke points





- 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 [®] , mm	Studies"	Formula	Name	NSP±CI, mm	Studies
Alkanes	200900	11/10 Select	234	CoHio	Cyclohexene	38.7±6.3	2-4,7,11
C2H6	Ethane	319±153	4,6	C6H12	1-Hexene	55.2±12.5	2-5,11
C3H6	Cyclopropane	25.9	4	C2H12	4-Methylcyclohesene	23.5	8
C ₃ H ₂	Propane	202±82	4,6	C2H14	1-Heptene	70.1±15.6	2-4
CaHin	n-Butane	175±33	4.6	CoH14	2-Heptene	73.8±11.0	3.4
CaHin	Isobutane	96.3	4	CaHia	1.S-Cyclooctadiene	20.0	8
CeHin	Cyclopertage	58.0±13.5	2-4.11	C.H.A	2 S-Dimethyl-1 S-hexadiene	11.8	4
CaHin	n-Pertane	163±25	2.4.5.9	CaHis	1-Octene	56.7±20.9	3.8.10.11
CeHin	Isoperitane	104	2	C.H.s	2-Octene	86.4	3
Cellin	2.2-DimetingIntoname	59.8	4	CoHus	1-Nomene	55.2	8
CHIA	Methylayclopentane	55 3+1 1	34	CueHue	Pinene	18.5	2
CHI	Curchherane	81 9+164	2.48911	CiaHaa	1-Deceme	72 4+180	2.4.8
CH	n-Hevane	149+24	34911	CuaHaa	1-Dodeceme	68 3+30 3	38
CH	2-Matharhant me	116+7	35	CuHar	1-Tridecene	55.2	8
CH	3-Methylpertane	124+12	34	CuHan	1-Tetradecerre	67.9+22.6	38
C.H.	2.2. Dimetherbart me	80 1+38 0	23	CuHa	1-Howadocomo	69 2+251	3.9
C.H.	2.3. Dimethyloutane	105	3	CurHus	1-Ortadecene	821	3,0
C.H.	Motherbarabher mo	56 6+142	2381112	L Albune	-octauecene	02.1	-
Caller	n-Hentano	139+15	2.58911	CaHa	Filmme	14 6+8 3	4.6
C.H.	2 Mathanhama	110	2-3,0,3,11	C.H.	Deserve	10.2	4,0
Callis	2 Mathematic	120	2	Cilla	1 Destroy	10.5	4
CH	2.3 Dhustladaustan	107	20	CH	1-Fertyre	11.0	4
CH	2.4 Dimethylpertare	102	2	Collin	1-Dexyne	19 4+0 9	0 11
CHIE	2,4-Dimensipertare	102	200	CHI	1-neptyne	21.1.0.2	0,11
Callis	Cis-1,3-Dimethykyclohexan	e 01.1	3	Cania	1-Octyne	21.1±0.2	3,8
CHIG	Conjugationexane	11.5±24.0	2,0	CIGHIS	1-Decyne	23.3	0
Canie	Cycloctane	122.00	2 6 11	C15U55	I-Lodecyne	51.4	2
Canis	n-Octanie	15/±28	5-5,11	Aromane	·	0.00.1.00	0.4.0.11.10
Callis	2-Methylheptane	120	2	CoHo	Benzene	8.79±1.00	2-4,7,11,12
Callis	3-Methylheptane	110	3	Calls	lohene	8.12±1.60	1,2-5,7,8-11
Cania	4-Methymeptane	102	2	CINI	Styrene	5.27±5.49	2,8
Callis	3-Ethylhexane	102	3	CzHin	Xylenes	8.10±1.62	1,2,3,7,8,11,
Callin	2,2-Dimethylhexane	87.3	3	CaHin	Ethylberzene	5.92±1.00	1,3,4,7,8
Callin	2,3-Dimethylhexane	107	3	CoHa	1-Phenyl-1-propyne	4.70	8
Cania	2,2,4-1 rimethy pertane	54.5±13.0	2,3,7,8-11,1.	Cons	Indene	5.99±0.25	3,8
Callia	2,3,4-Trimethylperitane	59.0	2	CoHin	a-Methylstyrene	6.09	10
Callis	2,2,3-Trimethylperitane	58.1	2	CoH12	Mestylene	5.24	3
Callis	2-Methyl-3-ethylpentane	89.0	3	CoHis	Immethylbenzenes	6.43±1.17	3,8,12
CoHao	72-Nonane	110±27	4,8	CoH12	Cumene	6.14±1.78	3,8
CoH20	Isononane	129	4	CoH12	n-Propylbenzene	6.86±1.90	3,4,8,12
CieHis	Decalm	25.5±4.3	1,2,3,7,8,12	CiaHz	Naphthalene	3.49	3
CieHas	n-Decane	122±14	3,5,8	CioHio	1,2-Dihydronaphthalene	5.57	12
C11H24	n-Undecane	113±23	3,8	C10H12	Tetralin	7.40±1.21	1,2,3,7,8,10,
C12H22	cyclohexylcyclohexane	42.9±8.8	2,3,8	CioHia	p-Cymene	7.90±2.84	2,3,7,8
C12H26	n-Dodecane	107±24	3,8	CioHia	n-Butylbenzene	7.39±2.12	3,8,10
C13H22	n-Tridecane	116	3	CinHia	sec-Butylbenzene	6.97±1.69	3,10
C14H30	n-Tetradecane	120	3	C10H14	tert-Butylbergene	4.37	3
C16H34	n-Hexadecane	110	2	C10H14	IsobutyIbenzene	7.41±2.54	3,10
C16H34	Isohexadecane	33.2	12	C10H14	Diethylbenzenes	6.11	3
Alkenes	A1228-010-02	5725010372M	076820	C11H10	1-Methyhaphthalene	5.14±0.48	1,3,7,8,12
C_2H_4	Ethene	120±18	4,6,9	CIIHIO	2-Methyhaphthalene	4.37	3
C ₃ H ₆	Propene	32.8±4.7	4,6,9	C11H15	sec-Pentylbenzene	6.98	3
C4H6	1,3-Butadiene	9.23±11.0	4,6	C11H16	tert-Pertylbenzene	6.98	3
C4H2	1-Butene	29.1	4	C11H16	n-Pertylberzene	10.6	8
C4Hz	2-Butene	30.7	4	C12H12	Dimethylnaphthalenes	4.37	3
C4Hz	Isobutene	22.6±7.4	4,6	C12H16	Cyclohexylbermene	7.67±1.06	3,8,10,12
CsHz	Cyclopertene	10.3	4	C12H12	Triethylbenzenes	4.37	3
CsHz	2-Methyl-1,3-but adiene	15.3	11	C12H12	m-Diisopropylbermene	10.6	2
CsHie	1-Pertene	47.1±9.2	2,4,11	C13H12	Benzylbenzene	4.35	10

FIRE

• 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).





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

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

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





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



Guo et al., AO 2013

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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:

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

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





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)	± 4×10 ⁻⁴	± 6×10 ⁻⁴
Uncertainty	± 30%	± 10%



or

56

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
- 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



gives Planck's Law the blackbody spectral emissive power:

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

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Integrating yields the total emissive (the power Stephan-Boltzmann Law): $E = \sigma T^4$

Wein displacement law: $\lambda_{\text{max}} = b / T$





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.









- 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 μ m 8 μ m there is atmospheric attenuation from H₂O and CO₂.



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







Single-band pyrometry





Kim and Sunderland (FSJ 2019)



Ratio pyrometry





Kim and Sunderland (FSJ 2019)





	Single-band Fyrometry	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 ετ 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:

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



Medtherm

The heat flux is:

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



Ember pyrometry with color camera







Heat fluxes of ember piles







Color image of ember pile

Temperature and heat flux

Tlemsani et al. (2023)

Thin-filament pyrometry

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

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

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

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

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







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.:

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



Schwarzchild equation



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

$$dI/dx = -\kappa I,$$

where κ = absorption coefficient, aka attenuation coefficient or extinction coefficient. This is the simplest RTE

Integrate, assuming constant *k*, 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.

 $0 \le \tau \le \infty$

 $\tau << 1 \leftrightarrow \rightarrow$ optically thin $\tau >> 1 \leftarrow \rightarrow$ optically thick



Radiation from flames



The spectral radiative power from a flame is:

$$E_{\lambda} = \varepsilon_{\lambda} \frac{C_{1}}{\lambda^{5} \left[\exp\left(\frac{C_{2}}{\lambda T}\right) - 1\right]}, \text{ where}$$
$$\varepsilon_{\lambda} = 1 - e^{-\kappa_{\lambda} L}$$

An integration over all λ yields

$$E = \sum \varepsilon_i \sigma T^4, \text{ with}$$
$$\varepsilon_i = 1 - e^{-\kappa_p p L}$$

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 $\chi_r = 15\%$ (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 λ	Rayleigh	Simple
Medium		Mie	Complex
Large	> 2	Geometric optics (ray tracing)	Simple



Soot extinction



• Rayleigh scattering for soot yields

 $\kappa_{\!\lambda}$ = 6 π $E(m)\,f_s\,/\,\lambda$,

with refractive index absorption function E(m) = 0.26for soot with a refractive index of m = 1.57 - 0.56 i

Note that soot emissivity also scales with 1 / λ .

• 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







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



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