Experimental Investigation on Soot Volume Fraction in an Ethylene Diffusion Flame by Emission Spectrometry without Optically-Thin Assumption

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Abstract. An improved soot diagnostics technique based on tomographic reconstruction of flame emission spectra has been developed for an axisymmetric laminar diffusion flame without optically-thin assumption. Emission from the flame is scanned along the horizontal lateral axis of flame at several altitudes above the burner. At each measurement position, the local line-of-sight flame emission spectra is collected by a spectrometry over a spectral range of 700-1100 nm. Inversion of these data through one-dimensional tomography using a three-point Abel inversion yields radial distributions of the soot radiation from which soot volume fraction profiles are extracted. Traditionally, this procedure was applied only in the optically-thin flames for which the self-attenuation term of emitted radiation is ignored. However, this self-attenuation term is considered by iterative calculations in the paper. The configuration of the investigation flame is similar to the flames reported in the literatures. The results by the conventional method is found to be almost twice to the results by the improved method. This discrepancy revealed that the optically-thin assumption for the flames will cause serious errors in the conventional method, and the improved method could overcome this deficiency effectively.

1. INTRODUCTION

The understanding of soot formation mechanisms and knowledge of soot distribution within combustion systems is a key factor in many areas of combustion research. Flame radiation, heat transfer properties, particulate emission from combustion systems, and combustion efficiency all depend upon soot formation. As a consequence, optical diagnostics are recommended for measurement of radiant emission from hot soot due to their non-intrusiveness (Kennedy, 1997). They are a key source of information on the soot concentration field in many combustion applications.

The most established method is based on light extinction, which is a path-integrated or line-of-sight technique that has been widely used to measure soot volume fractions in flames, and frequently associated with scattering measurement for the simultaneous determination of soot particle size and number density (Santoro et al., 1983; Dasch et al., 1991; Gulder et al., 1993; Choi et al., 1995; Greenberg et al., 1997; Konsur et al., 1999). The technique provides field-integrated values of the soot volume fractions and needs an inversion method to reconstruct its spatial distribution in non-uniform fields, e.g., the Abel inversion method, for axisymmetric configurations (Vest, 1979), whose pitfall and advantages have been discussed in detail by Snelling et al. (1999).
Other nonintrusive methods can also be used. Laser-induced incandescence (LII) of soot provides spatially and temporally resolved measurements of soot distribution (Queay et al., 1994; Shaddix et al., 1996; Mitrovic et al., 1998). It requires a calibration procedure based upon extinction measurements or gravimetric sampling for quantitative data of soot volume fraction distribution. Laser-induced fluorescence (LIF) is based upon measurements of the fluorescence of C2 molecules from vaporized soot (Bengtsson, 1991; Westblom, 1991; Bengtsson et al., 1995; Bengtsson, 1996).

Spectral flame emission measurements have also been employed to obtain soot concentration distribution. Hall et al. (1990) used single wavelength emission/transmission tomography to two-dimensional maps of soot concentration in laminar diffusion flame (Snelling et al., 2002). Two-color emission pyrometry is widely used in practical situations, especially for studies in internal combustion engines. (Sivathanu et al., 1991; Sivathanu et al., 1992; Klassen et al., 1990; Choi et al., 1994; Sivathanu, 1990; Xu et al., 1998). However, it only has provided data on spatially averaged soot concentration and its accuracy is significantly limited by the uncertainty in the emissivity model, which is based on knowledge of soot optical properties (i.e., refractive index). De Iuliis et al. used a multi-wavelength diagnostic method in which multiwavelength soot emission intensities were measured by a low resolution spectrophotograph, and optical tomography (Able inversion) was applied to reconstruct soot volume fraction distribution in an axisymmetric flame (Snelling et al., 2002). Ayranci et al. (2008) also performed FTIR emission spectrometry to measure line-of-sight intensity spectra emitted by a co-annular ethylene/air diffusion flame and infer soot volume profiles from tomographic reconstruction. Nevertheless, when the tomographic technique was applied, they did not consider flame absorption of radiation and neglected the self-absorption term in the path integral for line-of-sight emission intensity.

In this paper, the soot emission concentration measurement method is improved by introducing a correction procedure for flame absorption of radiation, focuses on the measurement for line-of-sight flame emission spectrometry within 700-1100 nm range on an axisymmetric ethylene/air diffusion flame. The paper presents descriptions of the experimental methodology in section 2 and a comparison of conventional soot volume fraction reconstruction method to our modulated method with the self-absorption term correction procedure in section 3. Finally, the accuracy of the modulated method is evaluated through comparisons of the results to previously published data for similar flames by Santoro et al. who used combined light extinction and scattering to measure the soot distribution (Santoro et al., 1983).

2. EXPERIMENTAL METHODOLOGY

2.1 Experimental Apparatus

The experimental setup is shown schematically in Fig. 1. A laboratory grade axisymmetric ethylene/air diffusion flame was used to perform emission spectrometry measurements. Radiation emission from soot in flame passes through an optical fiber and is directed to the entrance slit of a spectrometer. The both sides of fiber are designed elaborately, at the side near the flame the head of fiber is covered by a cylindrical cap with a small hole of 0.25 mm diameter in its center to pass the emission from flame and at the side near the spectrometer the end of fiber is attached to a splint which assembled on front of the entrance slit of the spectrometer. A cycloidal hole in the center of splint is designed by the size of the end of fiber to allow the radiation from the fiber passing and isolate the radiation from circumstance. Transverse resolution is defined by the 0.25 mm pinhole and the spatial angle is 2–3°. This design is very similar with Conventional Kurlbaum which can give fine longitudinal resolution. So did our design. The spectrometer slit is oriented vertically with a height of 1.5 mm and a width of 1.5 mm for all emission could be directed to spectrometer. Emission from the flame scanned along its horizontal lateral axis at several altitudes above the burner is collected over a spectral range from 700 to 1100 nm. At each position, the spectrometer processes emitted radiation to yield local line-of-sight flame emission spectra and is calibrated with a blackbody furnace. The blackbody furnace is calibrated...
against a standard photoelectric pyrometer and the uncertainty in the spectral radiance temperature is ±5K. This calibration allows the spectra to be scaled to units of absolute spectral intensity.

![Fig. 1 Schematic diagram of the experimental setup](image1)

The burner for the laboratory grade axisymmetric laminar diffusion flame pictured in Fig 2 is of similar design to that previously reported by the National Research Council of Canada and others. It consists of a 10.7-mm-inner-diameter fuel tube, centred in a 88.6-mm-diameter air nozzle. The air passes through packed beds of glass beads and honeycomb to smooth the flow and prevent flame instabilities. It is different from other similar experiments (Hall et al., 1990; Deluliis et al., 1998; Ayranci et al., 2008), in the present paper, the burner is fixed on the platform and the head of fiber with a cylindrical cap is attached to a motorized translation stage (MT-310, BOIF, China) that enable spatial exploration of the flame along vertical and horizontal directions. In other experiments, the burner is situated on micrometric positioning stages. In order to eliminate external air circulations, the burner is protected by a flexible steel mesh. An appropriate viewing port in the mesh provides optical access.

![Fig 2. Schematic cross-section of the burner](image2)
A blackbody furnace with 800-1800°C temperature range was used for calibration of emission spectra by replacing the burner with the blackbody. Calibration of the blackbody for operating temperatures was checked by a pyrometer with certified calibration.

The spectrometer used in this study is a 300mm focal length monochromator (Spectra-Pro-2300i, Acton, US). It features an astigmatism-corrected optical system, triple indexable gratings and triple grating turret. The SpectraPro-2300i includes a direct digital grating scan mechanism with full wavelength scanning capabilities. It can be configured for various spectral ranges from 185nm to far infrared with available gratings and accessories. The configuration for the range under consideration in this study is a Silicon based photodiode detector for use in the wavelength range of 400 to 1100nm.[Model:SI-440].

2.2 Experiment Conditions
The experiment parameters of the measurements are summarized in Table 1. The C2H4 fuel flow rate is set to 129 ml/min (21°C, 1 atm), and the air coflow is 189 l/min, producing an overventilated flame 6.5 cm in height, which is studied by many researchers (Santoro et al., 1983; Delulisi et al., 1998; Koylu et al., 1997). A larger airflow significantly reduced a relatively slow pulsing global instability that is characteristic of buoyant nonpremixed flames, but also reduced the visible flame height. This, in turn, truncated the spatial resolution of the experiments. For the reason that the soot emission spectrum which is well know to display continuum characteristics that can be adequately captured by low resolution measurements and the flame flickering would induce the possible dynamic changes for the recorded soot emission intensity during the long recording times required for higher resolutions, the spectrometer was set to a low spectral resolution of 2nm.

2.3 Calibration Methodology
The spectra recorded by the spectrometer needs to be calibrated so that the effects of instruments can be eliminated and measured instrument units can be related to physical units of intensity. Calibration is carried out by measuring spectra from a blackbody furnace in the present study. An instrument response function which is deduced from the theoretical evaluation of reference measurement enables relate the spectrum recorded in instrument units to emission intensity spectrum in physical units. Ayrancı et. al. (1994) described the detailed procedure and emission spectrum calibration presented in this study are based on the same principle as them.

| Spectrometer | Spectral range | Spectral resolution |
|--------------|----------------|---------------------|
|              | 700-1100nm     | 2nm                 |
| Number of scans | 200           | Total scan time     |
|               |                | 60s                 |

| Flame properties |
|------------------|
| Fuel             | Ethylene,C2H4  |
| Purity           | ≥ 99.99%       |
| Air flow rate    | 189l/min       |
| Luminous flame height | 65mm     |
| Fuel flow rate   | 129ml/min      |
| Horizontal spatial resolution | 0.25±0.1mm    |
| Vertical spatial increment | 20 ±0.5mm     |

3. THEORY
3.1 Conventional Soot Property Reconstruction Method
The reconstruction of internal flame temperatures from external, path-integrated intensity measurements has long been a problem of interest. In the spectral intervals where combustion gases
can be assumed to transparent, flame soot emits, absorbs and scatters radiation continuously along the spectra. This isolated radiative activity of soot enables its characterization from emission spectroscopy at certain wavelength intervals. The generalized path integral for line-of-sight soot emission intensity along a chord \( y \), crossing the flame at fixed lateral position, \( x \), as shown in Fig1 is given in Eq. (1) (Hall et al., 1990; Ayranci et al., 2008).

\[
I_{s,y}(x) = \int_0^y \left[ \alpha_{\lambda}(y) \cdot I_{s,y}(T(y)) \right] \cdot \exp \left[ -\int_0^y \kappa_{\lambda}^{ext}(y')dy' \right] dy
\]

where \( \kappa_{\lambda}^{abs} \) and \( \kappa_{\lambda}^{ext} \) are the local absorption and extinction coefficients, as follows from Rayleigh-Debye-Gans/polydisperse-fractal aggregate (RDG/PFA) theory of particle light scattering and extinction (Koylu et al., 1994a; Koylu et al., 1994b; Koylu et al., 1997), for primary particles in the Rayleigh range (\( \pi d/\lambda < 0.3 \)) in the present study, scattering will be negligible and \( \kappa_{\lambda}^{abs} = \kappa_{\lambda}^{ext} \).

\( I_{s,y}(T) \) is the Planck function

\[
I_{s,y}(T) = \frac{2 \pi \hbar c^2 / \lambda^5}{\exp(\hbar c / \lambda kT) - 1} \approx \left( 2 \pi \hbar c^2 / \lambda^3 \right) \exp(\hbar c / \lambda kT)
\]

where the Wien’s approximation is a valid representation for Planck’s distribution at present temperature and spectral range.

The term before the exponential, \( \kappa_{\lambda}^{abs}(y) \cdot I_{s,y}(T(y)) \), models the local radiation emission rate, and the exponential term, \( -\int_0^y \kappa_{\lambda}^{ext}(y')dy' \), models the attenuation experienced by this emitted radiation as it propagates to the detector side of the flame along the chord \( y \). In the conventional soot property reconstruction method, the flame which is studied usually is assumed to be optically thin flame, thus the attenuation of emitted radiation is ignored:

\[
\int_0^y \kappa_{\lambda}^{ext}(y')dy' \approx 0
\]

Assuming the medium is axisymmetric, the line-of-sight soot emission intensity at a fixed lateral position is modeled as

\[
I_{s,y}(x) \approx \int_0^y \left[ \kappa_{\lambda}^{abs}(y) \cdot I_{s,y}(T(y)) \right] \approx \int_0^y B(y)dy
\]

In the Rayleigh limit, the absorption coefficient of soot and its dependence on wavelength are

\[
\kappa_{\lambda} = 6\pi E(m) f_s / \lambda
\]

where \( f_s \) is the local volume fraction of soot and \( E(m) = \| \ln[(m^2-1)/(m^2+2)] \| \) is a function of wavelength dependent soot complex index of refraction for which the correct value is much debated (Koylu et al., 1994). If assuming \( E(m) \) is constant in the present spectral range and spatial domain, then substituting Eqs (2) and (5) in Eq(4) yields

\[
B_s(y) \equiv \left( 12 \pi \hbar c^2 / \lambda^3 \right) f_s(y)E(m) \exp \left( \hbar c / \lambda kT(y) \right)
\]

Taking natural logarithm of both sides and rearranging gives following linear function in the wavenumber

\[
N_s(y) = \ln[B_s(y)\lambda^2] = \{\hbar c / [kT(y)]\} \cdot (1/\lambda) + \ln[12 \pi \hbar c^2 f_s(y)E(m)]
\]

Spectral emission source term \( B_s \) is reconstructed from measured emission intensities in lateral domain by employing 1-D tomography and soot properties at each radial location is retrieval by performing linear regression to \( \ln[B_s(y)\lambda^2] vs. (1/\lambda) \) plot. Volume fraction is obtained from the intercept for a gray refractive index, \( m \).

### 3.2 Modulated Soot Property Reconstruction Method

Since soot is both a good emitter and absorber of radiation, a portion of the light emission radiation along the measurement chord is reabsorbed by soot particles. The percentage of emission attenuation is dependent on the position of the emitter along the chord through the flame (Snelling et al., 2002). In the development of the equations for tomographic inversion, the use of tomography in soot property measurements is based on the assumption that the percentage of emission re-absorption by soot is vary low, which is called optically thin as its optical thickness is vary small. When the optical thickness
beyond a critical value (almost 2 for Fourier transform reconstructive algorithm (Hall et al., 1990), errors started to appear. Strictly speaking, this means that emission measurements are not line integrals of a local property field as is required for tomographic reconstruction, because each emitter does not experience the same percentage attenuation, the line-of-sight measurements become technically unsuitable for tomographic inversion using the Abel inversion. Therefore, when the medium is not optically thin, corrections for the self-attenuation term in Eq.1 should be introduced. To these flames investigated in many papers (Hall et al., 1990; DeIuliis et al., 1998; Aranci et al., 2004), although their configuration is not the same, all of them are assumed to be optically thin flames and the self-attenuation term is ignored even if the relative large-size flame of which the fuel flow rate is set to the smoke point and the top soot volume fraction is up to 14 ppm (Aranci et al., 2004). As the reconstructive algorithms (Fourier transform or three-point Abel inversion algorithm, onion-peeling method and so on) is sensitive to the optical thickness, the optically thin flames assumption is not suitable in many experiment conditions and the self-attenuation term can be introduced by iterative calculation. The detailed procedure included the following 3 steps: 

1) Assuming the self-attenuation term is ignored, Eq.3 and Eq. 4 is established and the soot local volume fraction are obtained by the conventional reconstruction method. 

2) As particle light scattering is negligible in this paper, the value of self-attenuation term can be calculated out using the soot local volume fraction gained in Step 1, that is \[ \exp(-\int_r^\infty k(y')dy') = A. \]

3) Introducing the value of self-attenuation term A to the local property field \( I_x(x) \), thus Eq.1 changed to be \( I_x(x) = \int_0^\infty \left[ k_s(y)I_s[T(y)]\right]dy\cdot A \), since A is constant, the soot local volume fraction in Eq.(1) can be solved by conventional method. Then the new result will be taken back to Step 2 and a new iterative procedure from Step 2 to 3 will begin until it end up when the condition of convergence is satisfied. 

The condition of convergence in the present study is set to be less 0.001 ppm for the soot local volume fraction between two adjacent iterative results. 

For the one-dimensional tomography reconstructive algorithms performed on the data, there existed 4 approaches at least (three-point Abel inversion method (Dasch, 1992), Fourier transform (Hall et al., 1990), onion-peeling and filtered backprojection methods (Dasch, 1992)). Three-point Abel inversion algorithm is selected to deconvolve soot emission spectrometry projections as it was previously found to be more accurate and efficient to onion-peeling and filtered backprojection methods and less complicated data reduction procedures to Fourier transform.

4. RESULTS AND DISCUSSION

4.1 Blackbody Furnace and Flame Emission Measurements

Blackbody furnace measurements were carried out at blackbody temperatures from 1000 °C to 1500 °C of 20 °C interval which are expectedly close to flame temperature. Fig 3 depicts blackbody furnace spectra measured at 1200 °C and theoretical blackbody intensities obtained from Plank function. An iron covering attached to the window of blackbody furnace is made in particular for calibration to ensure background instrument emission spectra are measured to be null.

Calibrated flame emission intensity spectra of 800 nm wavelength collected at 3 vertical positions above the burner are displayed in Fig. 4. Evolution of lateral profiles with vertical position is displayed in Fig. 5 at 800nm wavelength which is adequate to represent the results within 700-1100nm range as the spectral variations are monotonic in this range. The intensity profiles confirm that the flame is acceptably axisymmetric.

4.2 Soot Volume Fraction Reconstruction without Self-Attenuation Term
The regression to $N_x$ versus wavenumber ($-1/\lambda$) plot at $x=0\text{mm}$, $z=30\text{mm}$ above the burner is displayed in Fig6. $N_x$ is linear relationship with ($-1/\lambda$) within 700–1000nm spectral range indicates the soot refractive index function $E(m)$ is constant in the present study. Consequently, the assumption that $E(m)$ is independent of wavelength is valid and a magnitude of 0.26 ($n=1.57$ and $k=0.56$ (Dalzell, 1959)) is acceptable in this paper.
Soot volume fraction profiles inferred by optically thin flame assumption are plotted in Fig7. The results are compared to LE(light extinction) measurements. C.P. Arana et al. (Aranci et al., 2004) used full-field light extinction to measure the soot distribution in various ethylene/air partially premixed flames (including nonpremixed flame), the structure of their burner is similar with ours and the size of investigated flame corresponds to our flame. they used three-point Abel inversion method to calculate soot volume fraction based on a constant E(m) value assumption, specially obtained two results using two different E(m) values. We chose the results of nonpremixed flame with the same E(m) value to compare. Since there is some discrepancy in the size of investigated flame between our and the earlier researchers, the results of lateral profiles at vertical position of the same H/F(height/flame size) ratio is chosen to compare.

![Graph](image1)

**Table 2 Comparison of the max soot volume fraction of our and Arana et.al’s data at three height above the burner**

| Heights | Max Volume Fraction |
|---------|---------------------|
|         | Without SAT (ppm)   | Arana et.al (ppm) |
| Z=10mm  | 1.4                 | 1.6               |
| Z=30mm  | 8.2                 | 9                 |
| Z=50mm  | 13.9                | 12                |

![Graph](image2)

**Fig. 7.Comparison of soot volume fraction distributions for a nonpremixed flame inferred by optically thin flame assumption with those of Arana et al.[33] at various heights above the burner.** (a) through (c), correspond respectively to HAB=10, 30 and 50mm

At z=10mm above the burner the inspection of soot volume fraction profile along the lateral axis indicates that flame contains no soot at the center but within an annular region at 2-4mm radius. This profiles are nearly flat at flame center and increase towards the flame edge. Our results at the flame
center were found to be in line with observations in the literature and the variation range of volume fraction are in good agreement with previously published data, only the small discrepancy lies in the location of peak temperature and volume fraction since the radial dimension of flame is not same between our and earlier studies. At higher locations of the flame, soot concentration increases but is still low around the flame axis. At $z=30$mm height, the maximum soot concentration is in the outer layer at 3mm radius. this trend changed gradually with height, at $z=50$mm above the fuel outlet, the centerline of flame is the region of maximum soot concentration. Along the axis a narrowing of the visible flame is observed, which is well described by the sequence of the soot profiles. The comparison of the max soot volume fraction of our and Arana et.al’s data at three height above the burner are shown in Table.2.

4.3 The Variation of the Value of Self-Attenuation Term

Fig. 8 shows the average value of self-attenuation term for the three heights at 800nm with attenuation correction applied in the first and second interation procedures. All values along the lateral axis at three height of flame before interation are less than 1. At $z=10$mm above the fuel tube, the self-attenuation term value is close to 1 due to the low soot volume fraction existed there, furthermore it changes a little after two interation procedures. Nevertheless, at $z=30$ and 50mm, the self-attenuation term value has a significant change between before and after interation procedures since there are higher soot volume fraction relatively. The observation of Fig. 8 obviously reveals that the self-attenuation term value is close to 1 after two interation procedures, which means that the error of the assumption of optically thin flame could decrease to a minimum value after our correction procedures.

Fig. 8 Comparison of the average value of self-attenuation term with one time of iteration (b) and two times of iterations (c) and without iteration (a) for the three heights at 800 nm.

4.4 Soot Volume Fraction Reconstruction with Self-Attenuation Term

In Fig. 9, the soot volume fraction with self-attenuation correction applied after two iteration procedures are shown. The profile is compared to previously published data by R.J.Santoro et.al, they used combined light extinction and scattering to measure the soot distribution in nonpremixed ethylene coflow flames, which is not related to optically thin and a $E(m)$ constant value assumption and has been extensively discussed in the literatures. Considering the different size of investigated flames, the results are in good agreement with earlier data. For example (Santoro et al., 1983), the maximum value for the soot volume fraction in the annular soot layer at $z=30$mm height ($H/F\approx 0.50$) is...
7ppm, whereas the present value was 5.5ppm, the error of LE measurement is ±0.5-1ppm. These two values are in best agreement within errors. The radial profile at z=30mm above the burner outlet reveals that the agreement of the variation trend and range along the lateral axis between our results and those by Santoro et.al (1983) is very good, the serious discrepancy is the data at z=50mm height, the region of maximum soot concentration is flame center for our result correspond to flame edge for data by Santoro et.al (1983).

Table 3 Comparison of the max soot volume fraction of our and R.J.Santoro et.al’s data at three heights above the burner

| Height | Max Volume Fraction |
|--------|---------------------|
|        | With SAT (ppm)      | R.J.Santoro et.al (ppm) |
| Z=10mm | 1.2                 | 1                         |
| Z=30mm | 5.5                 | 7                         |
| Z=50mm | 7.4                 | 9                         |

This is attributed to the different height of flame, which influence the results of the upper half of flame significantly. Table 2 summarizes the comparison of the max soot volume fraction of our and data by Santoro et.al (1983) at three heights above the burner. A comparison of soot volume fraction reconstruction with and without attenuation correction indicates that considering the self-attenuation...
term could reduce the value of soot volume fraction, these improve the measurement precision specially for the flames with higher soot loading.

5. CONCLUSIONS

An improved soot diagnostics technique based on tomographic reconstruction of flame emission spectra has been developed for nonintrusive characterization of soot volume fraction fields within an optically thick, axisymmetric laminar diffusion flame. Emission from the flame is scanned along the horizontal lateral axis of flame at several altitudes above the burner. At each measurement position, the local line-of-sight flame emission spectra is collected by the spectrometry over a spectral range of 700-1100nm. Inversion of these data through one-dimensional tomography using a three-point Abel inversion yields radial distributions of the soot radiation from which soot volume fraction profiles are extracted. With the conventional method, these procedures is applied only in the optically thin flames for which the self-attenuation term of emitted radiation is ignored, however, with our improved method, this self-attenuation term is considered by iterative calculations in the flames with no assumption of optically thin. The results by the conventional method are found to be in agreement with literatures but almost twice to the results by the improved method. The comparison of soot volume fraction reconstruction with and without attenuation correction indicates that considering the self-attenuation term could reduce the value of soot volume fraction, these improve the measurement precision specially for the flames with higher soot loading.

ACKNOWLEDGEMENTS

The present research was partially supported by the National Natrual Science Foundation of China (No. 50636010). Dr. Fengshan Liu from Combustion Technology Group, Institute for Chemical Process & Environmental Technology, National Research Council, Canada, helped author’s group to carry out combustion simulation and experiment work, is gratefully appreciated.

NOMENCLATURE

\( I \) \quad \text{radiation intensity} \quad [W/m^2/sr]  \\
\( l \) \quad \text{distance} \quad [m]  \\
\( d \) \quad \text{radiation intensity} \quad [W/m^2/sr]  \\
\( f_v \) \quad \text{soot volume fraction} \quad [ppm]  \\
\( m \) \quad \text{real part of the refractive index} \quad [/]  \\
\( n \) \quad \text{imaginary of the refractive index} \quad [/]  \\
\( T \) \quad \text{temperature} \quad [K]  \\

Greek Letters

\( \kappa \) \quad \text{absorption coefficient} \quad [m^{-1}]  \\
\( \lambda \) \quad \text{wavelength} \quad [nm]  \\

Subscripts

\( b \) \quad \text{black body}  \\

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