



## Spectral Study of the Smoke Optical Density in Non-flaming Condition

Julien Tissot, Martine Talbaut, Jérôme Yon, Alexis Coppalle, Alexandre  
Bescond

### ► To cite this version:

Julien Tissot, Martine Talbaut, Jérôme Yon, Alexis Coppalle, Alexandre Bescond. Spectral Study of the Smoke Optical Density in Non-flaming Condition. *Procedia Engineering*, 2013, 62, pp.821-828. 10.1016/j.proeng.2013.08.131 . hal-01613294

**HAL Id: hal-01613294**

**<https://hal.science/hal-01613294>**

Submitted on 7 Jun 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0  
International License

The 9<sup>th</sup> Asia-Oceania Symposium on Fire Science and Technology

## Spectral study of the smoke optical density in non-flaming condition

Julien Tissot<sup>a</sup>, Martine Talbaut<sup>a,\*</sup>, Jerome Yon<sup>a</sup>, Alexis Coppalle<sup>a</sup>, Alexandre Bescond<sup>a</sup>
<sup>a</sup>CNRS UMR 6614-CORIA, INSA de Rouen, Avenue de l'Université, BP12, Saint Etienne du Rouvray 76801, France

## Abstract

Optical properties of smokes have to be known because of their influence on visibility which can be reduced during evacuation of people and firemen intervention. Measurements have been carried out in non-flaming condition on smokes produced by solid materials exposed to an intensive radiation flux of 25 kW·m<sup>-2</sup>. Two materials have been studied: wood and PMMA. A smoke chamber has been used to perform measurements of transmittance and optical density of smokes on the visible wavelength spectrum as recommended by standards. To go further, spectral measurements and analysis of the smoke optical properties for wavelengths between 350 and 1125 nm have been carried out. In parallel, the mass concentration of the particles has been measured and it allows to determine the specific extinction coefficient. The spectral measurements have highlighted the dependence of the transmittance, the extinction coefficient and the specific extinction coefficient on the wavelength. The main features of the spectral results are discussed and compared to other studies. A mean value of the specific extinction coefficient on the visible spectrum is proposed and compared to other data.

© 2013 International Association for Fire Safety Science. Published by Elsevier Ltd. Open access under [CC BY-NC-ND license](#). Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology

**Keywords:** Smoke; Standard; Non-flaming condition; Optical density; Extinction coefficient; Spectral

## Nomenclature

|           |   |                      |   |
|-----------|---|----------------------|---|
| $t$       | time (s)  | $V$                  | box volume (m <sup>3</sup> )                        |
| $A$       | sample surface exposed to the radiation (m <sup>2</sup> ) | <i>Greek symbols</i> |   |
| $C$       | concentration (g/m <sup>3</sup> )                         | $\sigma_s$           | specific extinction coefficient (m <sup>2</sup> /g) |
| $D$       | optical density (-)                                       | $\lambda$            | wavelength (nm)                                     |
| $I$       | overall light intensity (-)                               | $\lambda_{max}$      | maximal wavelength detection of the PM (nm)         |
| $K_{ext}$ | extinction coefficient (m <sup>-1</sup> )                 | $\lambda_{min}$      | minimal wavelength detection of the PM(nm)          |
| $L$       | length of the light beam (m)                              | <i>Subscripts</i>    |   |
| $M$       | mass (g)  | $0$                  | initial   |
| $PMMA$    | poly(methyl methacrylate)                                 | $mass$               | mass  |
| $T$       | transmittance (-)   | $s$                  | specific  |
| $T_f$     | furnace temperature (°C)                                  | $\lambda$            | spectral  |

## 1. Introduction

The smoke produced during a fire is caused by the combustion of burning materials and by the pyrolysis of these materials which receive radiation of the flame. This smoke is a problem to the evacuation efforts and to firemen intervention because visibility decreases when the concentration of particles increases. In order to classify and to select the best suited materials for these situations, standard measurements of smoke optical density are performed. These measurements consist in exposing a material to a radiative flux in a box and in measuring the extinction of a light beam passing through the smoke

\* Corresponding author. Tel.: +33 232 959 817; fax: +33 232 959 780.

E-mail address: [martine.talbaut@coria.fr](mailto:martine.talbaut@coria.fr).

which accumulates in the smoke chamber (standards NFX 10-702 [1] and ASTM E 662 [2]). The transmission of this light beam is detected by a photomultiplier which integrates the light intensity on the visible spectrum. Transmittance, optical density and specific optical density can be deduced from these measurements to characterize material as specified in the standards.

With very high smoke concentrations, the transmittance decreases to very low values and the radiative transfer through the smoke is driven by the multiple scattering phenomenon. If such a phenomenon occurs, it is not possible to interpret the smoke transmittance without an exact calculation of the radiative transfer process. Jin [3] presents the results of the extinction coefficient for different wave lengths in the case of materials submitted to a radiation in smoldering and flaming conditions. These results show, in smoldering conditions, a decrease of this coefficient with decreasing wavelengths in the violet spectrum, while the simple diffusion theory predicts an increase [4]. Moreover, this decrease is observed for a larger wavelength range when the particles concentration increases. So the spectral measurements of the smoke extinction coefficient can give new information on that issue. Seader and Einhorn [5] propose, from optical density measurement performed inside a smoke chamber, a specific extinction coefficient of  $4.4 \text{ m}^2 \cdot \text{g}^{-1}$ . Knowing the value of this parameter, it is possible to determine, by using the Bouguer's law, the particle mass concentration from the measured value of optical density. It is interesting to know the physical meaning of this value averaged on the visible spectrum, and to check if this coefficient gives a good indication of the mean extinction coefficient for a given particle mass concentration [6, 7].

Consequently, the objective of this work is to carry out spectral measurements in complement of standard measurements on smokes in order to study the spectral dependence of the different parameters defined by the standard (transmittance, optical density...). It will allow to study the spectral evolution of the extinction coefficient for different particles concentrations. Finally, it will provide information concerning the averaged specific extinction coefficient in order to verify the relationship between extinction and particle concentration as proposed by Seader and Einhorn [5]. In this work, smoke is generated in a chamber according to the standard for two different solid material, wood and PMMA. The solid material is exposed to a radiative flux of  $25 \text{ kW} \cdot \text{m}^{-2}$ , creating smokes in non-flaming conditions. Standard and spectral measurements of the transmission of a light beam passing through the smoke are performed. For each test, the measurements are carried out at different times and smoke is sampled in order to measure the mass concentration of particles.

In the following sections, the experimental setup will be described for standard and spectral measurements. Then standards measurements will be analyzed in terms of specific optical density and transmittance. They will be compared to the spectral measurements. The spectral transmittance and extinction coefficient will be analyzed and compared to other data [3, 4, 8, 9]. Finally, a special attention will be paid to the specific extinction coefficient, which allows to deduce particle mass concentration from extinction measurements and a comparison with other works will be performed [5-7].

## 2. Experimental set up

### 2.1. Normative measurements

The measurement of the specific optical density of smoke is performed in a Smoke Box (ref NBS Smoke density chamber by Fire Testing Technology) represented on Fig. 1. In the sealed enclosure are disposed a furnace and a sample to burn. The furnace emits a radiative flux with a value  $25 \text{ kW} \cdot \text{m}^{-2}$  to the solid material sample which has a surface of  $65 \times 65 \text{ mm}^2$ . The smoke produced by the degradation of the material (without flame) is mainly composed of gases and particles. The accumulation of particles in the chamber over time causes an increase of the opacity. This is measured using a photometric device. We calculate the transmission of a light beam passing through smokes from bottom to top the chamber. A tungsten filament lamp is placed under the floor and separated to the chamber with a window. A lens allows transforming the light source in a collimated light beam of 38.1 mm diameter. It passes vertically through the smoke in the box and is collected above the chamber by a photo detector. In this photo detector, photons are focused on a photomultiplier of spectral sensitivity S-4 between  $\lambda_{\min}=160 \text{ nm}$  and  $\lambda_{\max}=680 \text{ nm}$ . Note that all the windows and lenses cut the spectrum below 350 nm. So, the measuring spectrum is in the visible range between 350 and 700 nm. The calculation of the overall transmittance  $T$ , the optical density  $D$  and the specific optical density  $D_s$  is achieved using respectively the following relations:

$$T = \frac{I}{I_0}, \quad D = \log\left(\frac{1}{T}\right), \quad D_s = \frac{V}{AL} D \quad (1)$$

where  $I$  is the overall light intensity measured at a given time,  $I_0$  the initial overall light intensity measured without smoke,  $V$  the volume of the box ( $V=0.5 \text{ m}^3$ ),  $A$  the sample surface exposed to the radiative flux ( $A=65 \times 65 \text{ mm}^2$ ), and  $L$  the length of the light beam ( $L=0.914 \text{ m}$ ).

In order to improve the measurement of the transmitted intensity, a filter system is placed before the photo multiplier.

The filter is a neutral density filter of value 2. It is used for measurement of transmitted light intensities between  $I_0$  and  $I_0/10000$ . For lower values than  $I_0/10000$  (*i.e.* for very low transmission of smoke), the filter is removed. This increases the signal measured by  $10^2$ . All the apparatuses composing the device are more finely detailed in the standards NFX 10-702 [1] and ASTM E 662 [2].

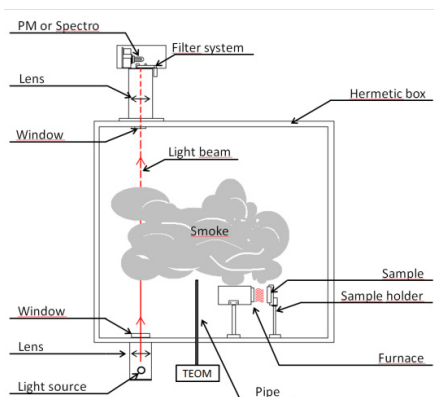


Fig. 1. Experimental setup of the smoke chamber.

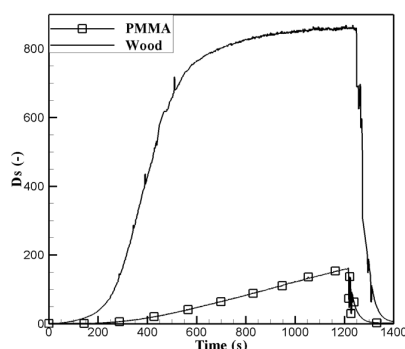


Fig. 2. Temporal evolution of the specific optical density for wood and PMMA smokes, measured with the smoke chamber.

## 2.2. Mass concentration measurements

The measurement of particle mass concentration is achieved thanks to a tapered element oscillating micro balance (TEOM series ref1105 by Rupprecht Patashnick Co.). This measurement is not part of the standard, therefore a change was made to the "normalized" system to collect the aerosol. A tube is placed in the chamber in order to sample particles. Then these particles are pumped out with a flow rate of  $3 \text{ L}\cdot\text{min}^{-1}$  and deposited on the TEOM filter. This deposit changes the oscillation frequency of the micro balance corresponding to the mass accumulated on the filter. The knowledge of the mass variation and of the sampling flow rate allows to determine the mass concentration of soot particles  $C_{mass}$ .

## 2.3. Spectral measurements

Measurements of extinction are performed on the same experimental setup as for standard measurements. It only replaces the photo multiplier by a spectrometer (ref: Maya2000Pro by Ocean Optics). The measured spectrum extends between 200 and 1125 nm with a resolution of about 0.5 nm. Note that the mass concentration and spectral measurements are performed in parallel.

# 3. Experimental results

## 3.1. Determination of the smoke opacity with photomultiplier (standard)

This section outlines opacities of two samples wood and PMMA according to standard ASTM E 662. This standard requires some handling conditions before and during the test which are specified in the ASTM E 662 [2].

In Fig. 2 are reported the temporal evolutions of the specific optical density for the wood and PMMA smokes in a non-flaming condition. The thickness of the samples is about 11 and 15 mm. The experimental conditions are identical for the two experiments. However, the relative humidity could not be maintained at the standard required value of 50 % [2]. In our case, the samples are conditioned in a room at  $23^\circ\text{C}$  (standard required value) and a relative humidity of 32 %.

For the wood, the specific optical density obtained with Eq. (1), equaling to 0 at the beginning of the test, increases slowly during the first 300 seconds, and then increases rapidly to obtain a plateau with a value near 860. This is explained by the increase of the smoke concentration in the box which induces a decrease of the visibility and the transmitted light and thus an increase of  $D_s$ . No minimum value of transmittance was observed during the test. So the duration of measurement is 20 min (as required by standard). The abrupt decrease of  $D_s$  at 1225 s corresponds to the end of this test which consists in stopping the exposition of the material to the heat flux and to evacuate the smokes of the chamber. The maximum value of

the specific optical density  $D_s$  is 861.5 and corresponds to a transmittance of  $3.6 \cdot 10^{-7}$  and an optical density of 6.4.

For PMMA, the transmittance is much higher than for wood and also corresponds to a much smaller specific optical density value. So the amount of accumulated smoke during pyrolysis of PMMA is much lower. On the one hand, since PMMA is less absorbing material, the rise of the sample temperature before it starts to be pyrolyzed is longer than for wood. On the other hand, when the pyrolysis is in steady state the amount of particles produced is much lower. Note that the irregularities in the specific optical density evolutions correspond to the change of the photomultiplier calibre and to the use of the filter system. Table 1 summarizes the results obtained for wood and PMMA at 600 and 1200 seconds. The experimental conditions are identical for the two experiments.

Table 1. Summary of the standard results for wood and PMMA at two times after the beginning of each test

|              | Wood                 |       | PMMA                 |       |
|--------------|----------------------|-------|----------------------|-------|
|              | Transmittance        | Ds    | Transmittance        | Ds    |
| 600 seconds  | $1.97 \cdot 10^{-6}$ | 766.2 | 0.44                 | 46.5  |
| 1200 seconds | $3.60 \cdot 10^{-7}$ | 861.5 | $6.28 \cdot 10^{-2}$ | 158.2 |

### 3.2. Transmittance spectral evolution of wood smoke

The transmittance has been measured in the visible spectrum with a scattering tungsten filament lamp and a photomultiplier. The transmitted signal through the smoke is integrated over a certain spectral range of the visible wavelengths as prescribed by the standard. It is interesting to study in more detail the optical characteristics of the smokes (transmittance, optical density, extinction coefficient ...) as a function of the wavelength.

To do that, the photomultiplier of the smoke chamber has been replaced by a spectrometer which measures the intensity of the light between 200 and 1125 nm.

During the test, the smoke is produced, which decreases the transmitted light to the spectrometer. The monochromatic transmittance  $T^\lambda$  is defined in Eq. (2) for each wavelength and the results are reported on Fig. 3. The range of values is very large, so for the small ones obtained at the beginning of the test the linear scale is chosen, and for the large ones obtained at long times, the logarithmic scale is used.

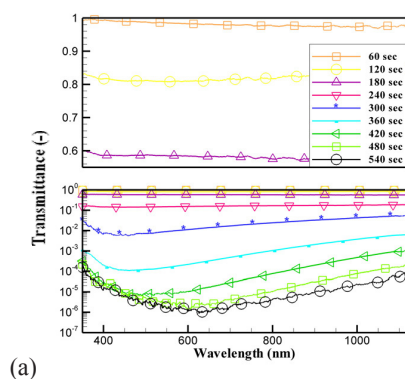


Fig. 3. Spectrum of the transmittance for different times after the beginning of the test on a wood sample.

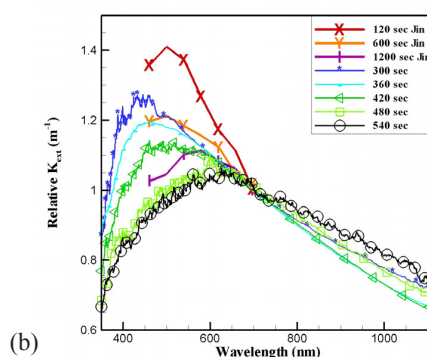


Fig. 4. Spectrum of the relative extinction coefficient (b, on the right) for different times after the beginning of the test on a wood sample. The relative extinction coefficient has been normalized with the extinction coefficient value obtained at 700 nm. Also reported the Jin's experimental value for smoldering smoke of wood (2002).

At the beginning of the test ( $t \leq 240$  s), the transmittance is more or less constant. This is not expected if the aerosols in the smoke are soot or composed of carbon matter [4, 9]. In this case the transmittance should increase strongly with the wavelength. With the present non-flaming conditions, it may be suspected that main content of smoke is a condensed phase in the form of small droplet suspended in air. The smoke looks like a fog, which has a slightly white color. This may be a mixture of oil, tar and water. A chemical analysis must be carried out to check the presence of these constituents.

After 300 s the transmittance varies with the wavelength. Looking from short to long wavelengths, the transmittance starts to decrease and then it increases. This pattern becomes more and more pronounced with the increase of smoke concentration over time. This can be explained by multiple scattering occurring when smoke concentration is high enough [4]. Indeed, the increase of the transmittance with decreasing wavelength in the violet spectrum highlights this affirmation. At short wavelengths, the optical cross section of droplets is great, and the multi-scattering process is enhanced, which produces an increase in the transmitted light on the axis of propagation, as seen in Fig. 3 for the long times.

For the PMMA, the results are similar showing similar spectral trends. However the minimum values for the transmittance are bigger, since the PMMA degradation produced less smoke as it has been shown previously.

### 3.3. Spectral evolution of the extinction coefficient of wood smoke

To better understand the effect of the wavelength on the optical properties of smoke, the spectral extinction coefficient  $K_{ext}^\lambda$  can be calculated from the previous transmission by using Bouguer's law:

$$K_{ext}^\lambda = \frac{1}{L} \ln \left( \frac{1}{T^\lambda} \right) \quad \text{with} \quad T^\lambda = \frac{I^\lambda}{I_0^\lambda} \quad (2)$$

It is important to note that this equation provides the true extinction coefficient only if there is no multiple-scattering in the transfer of light. Otherwise, one can always define an extinction coefficient with Eq. (2). However this one is not only a function of droplet properties along transmission axis, but it depends also of radiative transfer throughout the entire medium.

Due to the Eq. (2), the variation of  $K_{ext}^\lambda$  is the opposite of that of the transmittance. However, note that in the beginning of the tests, multiple scattering is not important. It would have been possible to calculate the  $K_{ext}^\lambda$  values using the Mie's theories if droplet properties were known (optical refractive index, sizes and concentration). Further analyses are needed in order to perform such calculations. However an estimation of the mean size of droplets is possible. It is well known that transmission through a fog is minimum (or the extinction coefficient is maximum) if droplet size equals to wavelength [8]. The results in Fig. 3 indicate that the droplet size is about 600nm, and thus inferior to the micron-meter. During each test, the mass of smoke inside the chamber increases, and so  $K_{ext}^\lambda$  values are also increasing. In order to better compare the spectral variation of  $K_{ext}^\lambda$  at the different times, it has been normalized by the value observed at 700 nm. The results have been reported in Fig. 4b. For wavelengths less than 600 nm, the spectra are very different. This can be explained once again by multiple-scattering. On the other side, for wavelengths greater than 600 nm, the differences are not so important and the extinction coefficient decreases with wavelength. This may be explained by the absorption process which seems to be important only if the mass concentration is high.

In Fig. 4, Jin's results obtained for smoke of wood and under smoldering condition, have been added [3]. It is interesting to note that the spectra are similar to the ones of present study. A maximum around 500 nm and large differences for the wavelengths below 700 nm are also observed.

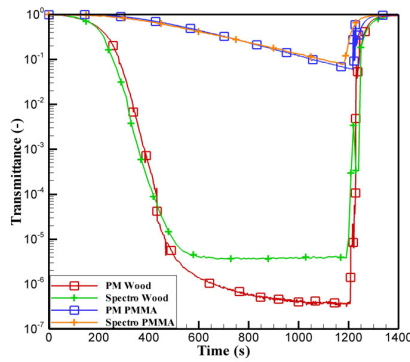
### 3.4. Comparison of the results obtained with the photomultiplier (normative results) and with the spectrometer (spectral measurements)

In this section, we compare the results obtained with the spectrometer and with the photo multiplier. The aim of this comparison is to ensure that the slight difference of optical efficiency between the two apparatus and that the TEOM aspiration for the mass concentration measurement does not change the result of the overall transmittance. Indeed, during the test, the TEOM aspiration modifies the concentration in the smoke chamber and consequently the transmittance. For duration of 20 min, the aspirated volume corresponds to 10% of the box volume.

For the spectrometer measurement, the spectral values of light intensity were integrated on the spectral range of the photo multiplier (between  $\lambda_{min}=160$  nm and  $\lambda_{max}=680$  nm) in order to determine an overall transmittance. This transmittance is determined by the following relationship:

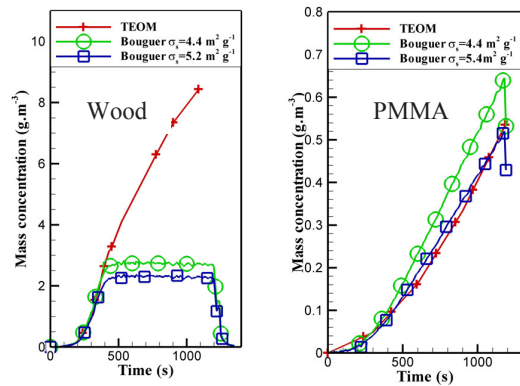
$$T = \frac{\int_{\lambda_{min}}^{\lambda_{max}} I^\lambda d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} I_0^\lambda d\lambda} \quad (3)$$





(a)

Fig. 5a. Comparison of temporal evolution of the overall transmittance with the photomultiplier and with the spectrometer for the wood and for the PMMA.



(b)

Fig. 5b. Temporal evolution of the mass concentration obtained with the TEOM and calculated with  $K_{ext}$  deduced of Bouguer's law and  $\sigma_s=5.2$  or  $5.4 \text{ m}^2 \cdot \text{g}^{-1}$  and  $\sigma_s=4.4 \text{ m}^2 \cdot \text{g}^{-1}$  [5] for the wood and for the PMMA.

Transmittances obtained with the two measurement systems are shown on Fig. 5a for wood and for PMMA. It is found that the trends are similar in both cases. The decrease is slow initially, and then becomes more and more significant. At 500 seconds for wood, the value is  $4 \times 10^{-6}$ , and at 1200 seconds for PMMA  $8 \times 10^{-2}$ . However, a gap appears on wood smoke transmittance for very low values of transmittance. This is due to the detection threshold of the measuring devices which are not the same for the both apparatus. Indeed, the sensibility and the measurement range of the photo multiplier are much higher than those of the spectrometer. So, when the transmittance is too low (less than  $4 \times 10^{-6}$ ), the spectrometer cannot detect this one and gives incorrect results while the photo multiplier is more precise in this range of transmittance. Despite this difference, results on Fig. 5a allow to conclude that, when the transmittance is not too low, the spectral measurements and measurements performed with the photo multiplier are in good agreement. It is possible to conclude that the aspiration of the mass measurement and the difference of optical efficiency between the two optical systems have no influences on the overall transmittance over the visible spectrum.

### 3.5. Particle mass concentration and specific extinction coefficient

In this section, we seek to determine a link between the aerosol mass concentration ( $\text{g} \cdot \text{m}^{-3}$ ) in the smoke and the extinction coefficient ( $\text{m}^{-1}$ ) via the specific extinction coefficient  $\sigma_s$  ( $\text{m}^2 \cdot \text{g}^{-1}$ ). The specific extinction coefficient  $\sigma_s^\lambda$  is calculated from the ratio between  $K_{ext}^\lambda$  and  $C_{mass}$  (the mass concentration obtained by the TEOM). Throughout the time of spectral measurements, mass measurements of particles are performed every second with the TEOM.

The results are presented on Fig. 6 for wood (a) and for PMMA (b). For wood, the specific extinction coefficient is between 3 and  $6.5 \text{ m}^2 \cdot \text{g}^{-1}$ ,  $\sigma_s^\lambda$  being dependent of  $K_{ext}^\lambda$ , the slope of the curves corresponds to the trend of  $K_{ext}^\lambda$ . At 120 seconds,  $\sigma_s^\lambda$  value is much larger, about  $12.7 \text{ m}^2 \cdot \text{g}^{-1}$ . This large difference with the others curves is caused by the mass concentration uncertainty when the amount of smoke is too low. After this time, the value of  $\sigma_s^\lambda$  decreases to achieve an average value of  $3.5 \text{ m}^2 \cdot \text{g}^{-1}$  at 420 s. The values obtained after 420 seconds cannot be taken into account. The reason is the limit of transmission measurement with the spectrometer as discussed previously in section 3.4. This does not permit an accurate calculation of  $\sigma_s$  if average transmission is less than  $8.9 \times 10^{-5}$ .

For PMMA, the spectral variations are the same and the specific extinction coefficients are between 3 and  $7 \text{ m}^2 \cdot \text{g}^{-1}$ . This result is surprising because wood and PMMA are two very different materials in terms of chemical composition. But, if the particles are oils or tars, these results show that the optical properties may be very close.

Table 2 summarizes the results for the wood and for the PMMA. At different times, are presented the measured transmittance  $T$ , the mass concentration  $C_{mass}$  and the specific extinction coefficient  $\sigma_{s \text{ m1}}$  given by the spectrometer and averaged on its spectral range (350-1125 nm).  $\sigma_{s \text{ m2}}$  is also given by the spectrometer but averaged on the spectral range of the standard measurements (350-680 nm). It is observed that for the two studied spectral ranges, the difference between the specific extinction coefficients is important and as high as 40%. So it is important, when one uses an average specific extinction coefficient, to specify the spectral range over which it is defined.

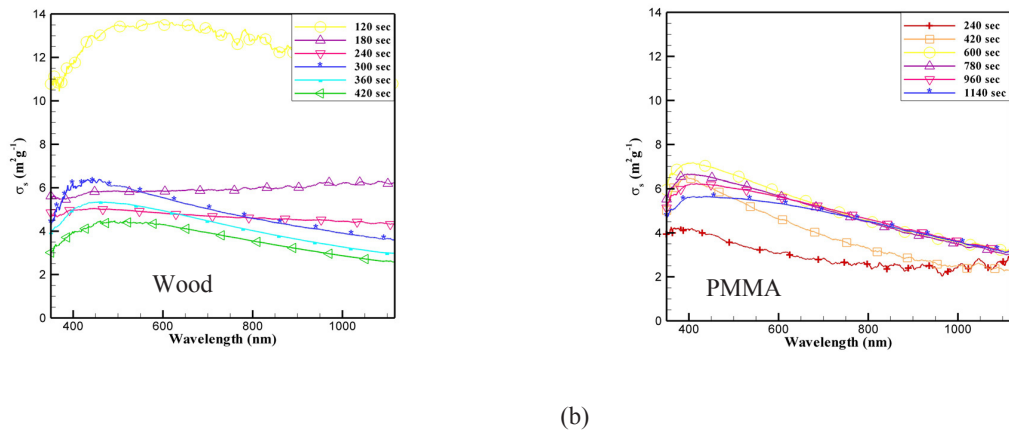


Fig. 6. Spectrum of the specific extinction coefficient for wood on the left and for PMMA on the right for different times after the beginning of the test.

In the case of smoke produced in a smoke chamber by pyrolysis of materials such as wood or PMMA, Seader and Einhorn [4] obtained a specific extinction coefficient of approximately  $4.4 \text{ m}^2 \cdot \text{g}^{-1}$ . Our  $\sigma_{\text{sm}1}$  results are close to Seader and Einhorn's value. However our  $\sigma_{\text{sm}2}$  values (obtained in the same spectral range that Seader and Einhorn) are always higher than the value obtained by Seader and Einhorn. In our case the mean value of specific extinction coefficient  $\sigma_{\text{sm}2}$  is 5.2 and  $5.4 \text{ m}^2 \cdot \text{g}^{-1}$  respectively for wood and for PMMA. So it is interesting to compare the mass concentration provided by our mean specific extinction coefficient to that given by Seader and Einhorn.

Table 2. Summary table of the results for wood and PMMA at four times after the beginning of each test

|         | Wood    |  |  |  |          | PMMA    |  |  |  |
|---------|---------|--|--|--|----------|---------|--|--|--|
|         | $T$ (-) | $C_{\text{mass}}$ ( $\text{g} \cdot \text{m}^{-3}$ ) | $\sigma_{\text{sm}1}$ ( $\text{m}^2 \cdot \text{g}^{-1}$ ) | $\sigma_{\text{sm}2}$ ( $\text{m}^2 \cdot \text{g}^{-1}$ ) |          | $T$ (-) | $C_{\text{mass}}$ ( $\text{g} \cdot \text{m}^{-3}$ ) | $\sigma_{\text{sm}1}$ ( $\text{m}^2 \cdot \text{g}^{-1}$ ) | $\sigma_{\text{sm}2}$ ( $\text{m}^2 \cdot \text{g}^{-1}$ ) |
| 180 sec | 5.8 e-1 | 2.2 e-2  | 6.0  | 5.8  | 300 sec  | 8.4 e-1 | 4.8 e-2  | 3.6  | 4.7  |
| 300 sec | 2.0 e-2 | 9.4 e-1  | 4.7  | 5.7  | 600 sec  | 4.2 e-1 | 1.6 e-1  | 5.0  | 6.5  |
| 360 sec | 9.6 e-4 | 2.0  | 4.1  | 5.0  | 900 sec  | 1.8 e-1 | 3.3 e-1  | 4.8  | 6.0  |
| 420 sec | 8.9 e-5 | 3.0  | 3.5  | 4.1  | 1200 sec | 7.7 e-2 | 5.4 e-1  | 4.4  | 5.3  |
|         |         | Mean coef :  | 4.4  | 5.2  |          |         | Mean coef :  | 4.3  | 5.4  |

To calculate this mass concentration from measured extinction coefficient  $K_{\text{ext}}$ , we use Eq. (4). The  $K_{\text{ext}}$  coefficient is deduced from the overall transmittance  $T$  ( $T$  is calculated from spectral values using Eq. (3)), with Bouguer's law:

$$C_{\text{mass}} = \frac{K_{\text{ext}}}{\sigma_s} \quad \text{with} \quad K_{\text{ext}} = \frac{1}{L} \ln \left( \frac{1}{T} \right) \quad (4)$$

Bouguer's law is valid only for monochromatic light and the light source used for extinction measurement is polychromatic. Moreover, when the phenomenon of multiple scattering appears, the physical meaning of  $K_{\text{ext}}$  is not simple. However Mulholland [6] and Putorti [7] specify that this specific extinction coefficient can still be used for an indication of the mass concentration.

Fig. 5b shows, for wood and PMMA, the mass concentration obtained with the TEOM and the concentrations calculated with  $\sigma_s = 4.4 \text{ m}^2 \cdot \text{g}^{-1}$  and  $\sigma_{\text{sm}2} = 5.2$  or  $5.4 \text{ m}^2 \cdot \text{g}^{-1}$  respectively to the Seader and Einhorn's coefficient and our mean coefficients.

For wood, the concentration obtained with the TEOM increases with time and reaches the value  $8.4 \text{ g} \cdot \text{m}^{-3}$  at 1088 seconds. There are two phases in the concentration increase. A first phase is between 0 and 300 seconds where the material undergoing radiation warms up and produces little smokes. In this phase, the increase is exponential. Then a second phase occurs between 300 and 1088 seconds where the evolution of the concentration is almost linear. The smoke production is thus constant. The results from Bouguer's law are in good agreement with that of TEOM's until about  $1.5 \text{ g} \cdot \text{m}^{-3}$ . Then a difference appears, the measured concentration continues to increase whereas the calculated concentration from the specific extinction coefficient stagnates. This difference can be due to the detection threshold of the spectrometer or to multiple scattering. Indeed, these two reasons can induce an underestimation of  $K_{\text{ext}}$  and consequently  $C_{\text{mass}}$ . In the beginning of the



test, the difference between the two concentrations obtained with Bouguer's law is not large. For a mass concentration between  $1.5 \text{ g}\cdot\text{m}^{-3}$  and  $3 \text{ g}\cdot\text{m}^{-3}$ , the concentration predicted with the Seader and Einhorn's coefficient continues to grow although the phenomenon of multiple scattering is already present. Therefore, we can conclude that Seader and Einhorn's coefficient slightly overestimates the mass concentration and so a value of  $5.2 \text{ m}^2\cdot\text{g}^{-1}$  is preferable.

For PMMA, there is a good agreement between the concentration obtained by Bouguer's law with  $\sigma_{\text{sm}2} = 5.4 \text{ m}^2\cdot\text{g}^{-1}$  and the TEOM's concentration. The results obtained with Seader and Einhorn's coefficient overestimates the concentration. In this test, the range of mass concentration is too low to explain that the difference is due to the detection threshold of the spectrometer or to multiple scattering. So for this range of mass concentration,  $\sigma_{\text{sm}2} = 5.4 \text{ m}^2\cdot\text{g}^{-1}$  is better than  $4.4 \text{ m}^2\cdot\text{g}^{-1}$ .

The specific extinction coefficient depends on the studied spectral range. It can be used for a not too large mass concentration ( $<1.5 \text{ g}\cdot\text{m}^{-3}$ ), in order to avoid multiple scattering and detection threshold problems. So in the standard spectral range, the mean specific extinction coefficient is equal to a mean value of  $5.3 \text{ m}^2\cdot\text{g}^{-1}$  for wood or PMMA.

#### 4. Concluding remarks

An experimental study on optical properties of smoke has been carried out in a smoke chamber. The samples of solid material, wood and PMMA, are exposed to an intensive radiation flux of  $25 \text{ kW}\cdot\text{m}^{-2}$  which generates smoke without flame (non-flaming condition). Added to the standard measurements, spectral variations of the transmitted light have been analysed with a spectrometer in the range of 350-1125 nm. In parallel, mass concentration has been measured and allows to determine the specific extinction coefficient in function of wavelength. The main conclusions are the followings:

- There is a very large difference between wood and PMMA: the transmittance of smoke is 20,000 times lower for wood than for PMMA due to a stronger formation of smoke for wood (after 20 min of smoke emission, the concentration of smoke is 20 times higher for wood than for PMMA).
- The extinction coefficient, defined from the transmittance value, is more or less constant in the visible spectrum for small particle concentrations. For high concentration of smoke and for short wavelengths, it increases with the wavelength. This can be explained by the multiple-scattering process which cannot be neglected at small wavelengths.
- The spectral evolution of the specific extinction coefficient can be deduced from the measurement of the extinction coefficient and mass concentration. Wood and PMMA smoke have more or less the same spectral variation. A mean value of  $5.3 \text{ m}^2\cdot\text{g}^{-1}$  has been determined.
- Despite the variation of this coefficient with the wavelength, our mean value gives a good approximation of the particle mass concentration only for a mass concentration which is not too high (smaller than  $1.5 \text{ g}\cdot\text{m}^{-3}$ ).

To complete these results it will be interesting in future work to do the same study in flaming condition. Another point will be to perform measurements of aerosol size distribution.

#### Acknowledgements

This work is financed by the Aircraftfire-FP7-265612 European project. The authors are also grateful to the LCPP (Laboratoire Central Préfecture de Police) for the material support. The authors wish to thank colleagues for their help: A. Si-Xian Loo and C. Jouen.

#### References

- [1] X 10-702-2, 1994. Détermination de l'opacité des fumées en atmosphère non renouvelée, Agence française de normalisation.
- [2] ASTM E 662, 2009. Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials, American Society for Testing and Materials; Philadelphia, 1997.
- [3] Jin, T., 2002. Visibility and Human Behavior in Fire Smoke, in "SFPE Handbook of Fire Protection Engineering", 3rd ed. Society of Fire Protection Engineers, Boston, pp. 2-42.
- [4] Modest, F. M., 2003. Radiative Heat Transfer, 2nd ed. Academic Press.
- [5] Seader, J. D., Einhorn, I. N., 1976. Some Physical, Chemical, Toxicological and Physiological Aspects of Fire Smokes. Proceedings of the Combustion Institute 16, p. 1423.
- [6] Mulholland, G., 2002. Smoke Production and Properties, in "SFPE Handbook of Fire Protection Engineering", 3rd ed. Society of Fire Protection Engineers, Boston, pp. 2-258.
- [7] Putorti, A. D., 1999. Design Parameters for Stack-Mounted Light Extinction Measurement Devices. NISTIR 99-6215, National Institute of Standards and Technology Gaithersburg.
- [8] Coppalle, A., Nedelka, D., Bauer, B., 1993. Fire Protection: Water Curtains. Fire Safety Journal 20(3), p. 241.
- [9] Yon J., Lemaire R., Therssen E., Desgroux P., Coppalle A., Ren K. F., 2011. Examination of Wavelength Dependent Soot Optical Properties of Diesel and Diesel/Rapeseed Methyl Ester Mixture by Extinction Spectra Analysis and LII Measurements. Applied Physics B, DOI 10.1007/s00340-011-4416-4.