International Journal of Heat and Mass Transfer 61 (2013) 742–748

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental study of radiative heat transfer in a translucent fuel sample exposed to different spectral sources

N. Bal [a,b,*], J. Raynard [a,c], G. Rein [a,d], J.L. Torero [a,e], M. Försth [f], P. Boulet [g], G. Parent [g], Z. Acem [g], G. Linteris [h]

[a] BRE Centre for Fire Safety Engineering, University of Edinburgh, King's buildings, EH9 3JN Edinburgh, UK
[b] Centre d'Etudes et de Recherches de l'Industrie du Béton, 1 Rue des Longs Réages, CS 10010, 28233 Epernon, France
[c] Airbus Operation SAS, 316 route de Bayonne, 31060 Toulouse Cedex 9, France
[d] Imperial College, London SW7 2AZ, UK
[e] The University of Queensland, QLD 4072, Australia
[f] SP Technical Research Institute of Sweden, Fire Technology, Box 857, SE-501 15 Borås, Sweden
[g] LEMTA, University of Nancy, CNRS, Faculté des Sciences et Techniques, BP 70239, 54506 Vandoeuvre lès Nancy Cedex, France
[h] Fire Science Division, National Institute of Standards and Technology, 100 Bureau Dr., Stop 8665, Gaithersburg, MD 20899-8665, USA

ARTICLE INFO

Article history:
Received 27 June 2012
Received in revised form 17 January 2013
Accepted 6 February 2013

Keywords:
Radiation
PMMA
Absorbance
Attenuation
Spectral dependence

ABSTRACT

Radiative heat transfer to a solid is a key mechanism in fire dynamics, and in-depth absorption is especially of importance for translucent fuels. The sample-heater interaction for radiative heat transfer is experimentally investigated in this study with two different heaters (electric resistance and tungsten lamp) using clear PolyMethylMethAcrylate (PMMA) samples from two different formulations (*Plexiglass* and *Lucite*). First, the significant effects of the heater type and operating temperature on the radiative heat transfer are revealed with broadband measurements of transmittance on samples of different thicknesses. Then, the attenuation coefficient in Beer–Lambert's law has been calculated from detailed spectral measurements over the full wavelength range encountered in real fires. The measurements present large spectral heterogeneity. These experimental results and calculation of in-depth absorption are used to explain the reason behind the apparent variation of the fuel absorbance with the sample thickness observed in past studies. The measurement of the spectral intensity emitted by the heaters verifies that the common assumption of blackbody behavior is correct for the electric resistance, whereas the tungsten lamp does not even behave as a greybody. This investigation proofs the necessity of a multi-band radiation model to calculate accurately the fire radiative heat transfer which affects directly the in-depth temperature profiles and hence the pyrolysis process for translucent fuel.

1. Introduction

Heat absorption in solid fuels is a key mechanism in fire growth (ignition and flame spread) [1]. Bench-scale fire tests based on radiative heating have been developed in order to rank different fuels according to their flammability (e.g. Cone Calorimeter [2], Fire Propagation Apparatus (FPA) [3]). In these tests, the incident radiation on the fuel sample is generally thought to be well known by virtue of assuming that the heat flux is emitted by a blackbody and received at the sample's free surface with a constant absorptivity coefficient close to unity. These assumptions allow characterizing the incident heat flux simply by means of a heat flux meter.

Past studies have challenged this assumption of total absorption by varying the type of heater [2–6], the distance heater-sample [6], the sample orientation [5] or by adding carbon coating [7]. These studies have revealed that the radiative heat transfer between the heater and the sample, which is essential for the understanding of pyrolysis and fire, is dependent on the experimental set-up.

Few experimental studies attempted to characterize the material radiative properties of most common fuels. Hallman [4] measured the spectral absorbance α_λ for 36 polymers up to 6.5 μm under different incidence angles and for two thicknesses (3.175 and 1.27 mm). The variations observed by Hallman [4] in the measurements of the ignition delay time when using two different heat sources (tungsten lamp or benzene flame) were explained by the spectral distribution of the absorbance.

Försth and Roos [8] measured α_λ for 62 materials (6 mm thick samples) over a wavelength range [0.3–20 μm]. Given the spectral intensity emitted by the source J_λ, they estimated the broadband effective absorbance $\bar{\alpha}$ with Eq. (1):

$$\bar{\alpha}(L) = \frac{\int_0^\infty \alpha_\lambda(L) J_\lambda(T) \mathrm{d}\lambda}{\int_0^\infty J_\lambda(T) \mathrm{d}\lambda} \quad (1)$$

* Corresponding author at: Centre d'Etudes et de Recherches de l'Industrie du Béton, 1 Rue des Longs Réages, CS 10010, 28233 Epernon, France. Tel.: +33 2 37 18 48 00.
E-mail addresses: n.bal@ed.ac.uk, n.bal@cerib.com (N. Bal).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.02.017

Nomenclature

J	intensity of emitted radiation
L	thickness
$\dot{q}''$	heat flux
r	reflectivity
T	temperature

Subscripts

0	incident flux
BACK	flux at the back surface
FRONT	flux at the front surface

λ	wavelength
τ	transmitted flux

Greek symbols

α	absorbance
κ	attenuation coefficient
ρ	reflectance
τ	transmittance

where λ is the wavelength, T the heater temperature and L the sample thickness.

Equivalent expressions of Eq. (1) can be developed for the effective transmittance $\bar{\tau}$ and reflectance $\bar{\rho}$ respectively based on their spectral distribution τ_λ and ρ_λ.

Försth and Roos [8] specified J_λ assuming blackbody behavior for a conical electric resistance (operating temperature between 674 and 1300 K providing a heat flux between 10 and 100 kW/m^2). Using their spectral measurements of α_λ, they observed a weak dependency of $\bar{\alpha}$ to the heater temperature (e.g. for clear PolyMethylMethAcrylate (PMMA) $0.87 < \bar{\alpha} < 0.93$).

In general, as a first approximation [8,9], the emitter is considered to behave as a blackbody and J_λ is therefore expressed by Planck's law. If no spectrally resolved measurements are available, α_λ is commonly considered constant over given wavelength bands. As an example, Siegel [10] divided the spectral domain of α_λ for glass materials into two bands: below a cut-off wavelength λ_C, α_λ is taken null whereas above λ_C, it is assumed equivalent to unity. These assumptions for J_λ and α_λ are strong and they will be reconsidered in this work.

Linteris et al. [9] measured α_λ over [1.5–15.1 μm] for 11 thermoplastics using samples with L lower than 3.5 mm. They estimated $\bar{\tau}$ through the sample as a function of L using an equivalent expression to Eq. (1). Moreover, they studied the ratio of radiative fluxes $\dot{q}''_\tau/\dot{q}''_0$ (where $\dot{q}''_\tau$ is the radiative flux transmitted through the sample and $\dot{q}''_0$ the incident flux on the free surface - see set up in Fig. 1). This ratio $\dot{q}''_\tau/\dot{q}''_0$ is equivalent to $\bar{\tau}$ in Eq. (1) with the approximation that the view factor of the source to the top surface is equal to the view factor of the source to the back surface [11]. Linteris et al. [9] observed, using a conical electric resistant, discrepancies between $\bar{\tau}$ and $\dot{q}''_\tau/\dot{q}''_0$ that were assumed to be the consequence of the narrowness of the spectral range explored. They show also that most of the radiation (>80%) is absorbed in-depth over a thin layer (~1 mm for clear PMMA). Moreover, they also observed that $ln(\dot{q}''_\tau/\dot{q}''_0)$ varies non-linearly with L, indicating that Beer–Lambert's law [11] is not satisfied broadband.

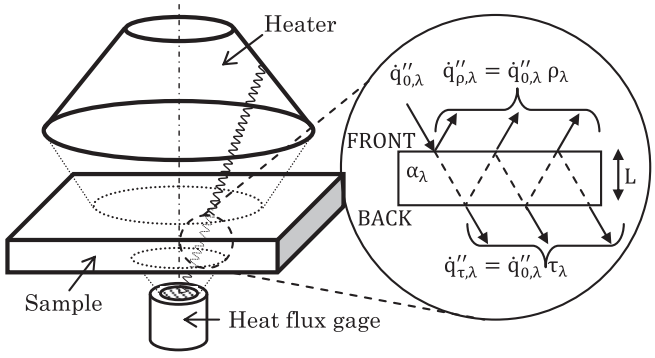

Fig. 1. Experimental set-up of the heat source, the sample and the heat flux meters. Insert: Schematic of the multiple reflection mechanism.

The present problem of radiative heat transfer through a semi-transparent medium is not a new topic, especially for none reacting materials such as glass [10] for which the heterogeneity of the radiative material properties has to be considered in engineering application.

However, most of previous investigations on radiative heat transfer to reactive solid fuel have been performed with a conical electric resistance as heat source, whereas other sources are used in flammability tests such a benzene flame [4] or tungsten lamps in the FPA [5,11–14]. Most recently, Girods et al. [12] conducted pyrolysis experiments on clear PMMA and wood samples using two of these sources: tungsten lamp and electrical resistance. They showed that the pyrolysis behavior (characterized by mass loss rate and temperature distribution) is strongly dependant on the heater type and that it is essential to better understand the physical mechanism of in-depth heat absorption through fundamental measurements.

Standard ignition tests attempt to eliminate the impact of the radiative material properties by adding a carbon coating on the free surface. This procedure is used to justify the assumption that the absorptivity equals to 1.

Bal and Rein [14] recently demonstrated that this hypothesis of full absorption by the black coating is incorrect. They found that around 65% of the radiation is transmitted through the carbon coating layer and is absorbed in-depth. Linteris et al. [9] further supported that even material with a high absorbing power can transmit through small layers a non-negligible fraction of the incident radiation (around 60% with black PMMA samples thinner than 0.2 mm).

Moreover, during an actual ignitability test, the added layer deteriorates before ignition occurs, increasing the complexity of its role.

When a solid is exposed to thermal solicitations, its surface appears visually often to darken (especially after ignition). As a consequence, the absorptivity from the visible part of the spectrum (irradiations typically emitted by very high temperature sources) will increase with the exposure time. However, when the irradiation is in the infrared, the situation is more unclear since darkening in the visible part of the spectrum does not necessarily imply darkening in the infrared part. As an example, Försth and Roos [8] have shown that while the absorbance in the visible is increased, in the infrared, the absorbance might slightly decrease for some materials, such as Acrylonitrile Butadiene Styrene (ABS) or plywood. The full absorption of the incident radiation after ignition is therefore not necessarily guarantee.

Thus, a detailed characterization of the radiative heat transfer through the material is of importance in pyrolysis for translucent fuels, even in the presence of carbon coating.

While the flammability results extracted from standard fire tests (e.g. time to ignition or ignition temperature) are commonly used for the calculation of fire growth, the differences in radiative heat transfer between the standard tests themselves are largely ignored. This paper investigates experimentally the radiative heater-sample interaction by using the heat sources of the two most important flammability bench-scale apparatuses (tungsten lamp and electric resistance) on two types of clear PMMA samples (*Plexiglass* and *Lucite*) over a range of sample thicknesses. PMMA has been chosen since it represents a reference material in fire tests resulting in a large number of experimental and numerical studies available in the literature. Moreover, the heterogeneity observed in the spectral distribution of its absorbance is representative for a large number of translucent polymers [4,8,9].

2. Broadband measurements of the sample transmittance

The ratios $\dot{q}''_\tau / \dot{q}''_0$ of transmitted to incident radiative heat fluxes were measured for clear PMMA samples of different thicknesses when exposed to a tungsten lamp and an electrical resistance. A heat flux gage was used to measure $\dot{q}''_\tau$ and $\dot{q}''_0$ following a methodology similar to that in Linteris et al. [9] (Fig. 1).

The tungsten lamp heater is made of six tubular quartz bulbs filled with halogen gas placed in a rectangular-shaped enclosure with a quartz window. The resistance heater is a truncated cone made of electric coils. Both heaters, positioned normal to the free surface, were set to provide 20 kW/m^2 at the centre of the sample's free surface. This heat flux level is achieved for the resistance when located 25 mm away from the sample and with the coil temperature sets at 858 K (controlled by a proportional integral-derivative device). The heat flux level is reached for the lamp when located 160 mm from the sample and with the filament at 2610 K (data based on the operating voltage from manufacturer for only one lamp). These heat flux levels and heater positions correspond to typical conditions used in bench scale fire tests.

The samples of PMMA used come from two different suppliers and are sold under the commercial names of *Plexiglass* and *Lucite*. Samples from both extruded and cast manufacturing processes are explored. In total, ten different thicknesses from 0.375 to 51 mm were tested.

The ratios $\dot{q}''_\tau / \dot{q}''_0$ measured and reported on Fig. 2 as a function of the sample thickness L, correspond to averages over three consecutive tests (lasting only a few seconds each). The maximum deviation from the average was 0.045 for the electric resistance and 0.03 for the lamp.

Given that the radiation sources are not collimated, the heat flux continuously decays with distance from the source. Therefore, the potentially absorbed heat flux $\dot{q}''$ is neither the incident heat flux measured at the distance of the free surface $\dot{q}''_{0FRONT}$, nor the one measured at the distance of the back surface (without sample) $\dot{q}''_{0BACK}$, but it is in-between these two. The true ratio is therefore inside in the range $\{\dot{q}''_\tau/\dot{q}''_{0FRONT}; \dot{q}''_\tau/\dot{q}''_{0BACK}\}$, represented in Fig. 2 by the dashed area for 20 kW/m^2. The good repeatability of the measurements is also visible Fig. 2 (e.g. *Lucite* for *L* equals 9 or 20 mm).

Fig. 2 shows that $\dot{q}''_\tau / \dot{q}''_0$ decreases non-linearly with *L*, and that the trend is different for each heater. A 1 mm thick sample exposed to 20 kW/m^2 with the lamp transmits between 63 and 69% of the incident heat flux, while only 9 to 10% is transmitted with the resistance. For a 50 mm sample (typical upper size in bench-scale testing), more than 20% of the lamp radiation is transmitted through the sample, and less than 1% for the resistance.

In-depth radiation heat transfer is not significantly affected by the formulation (*Lucite*/*Plexiglass* Fig. 2) or by the manufacturing process (cast/extruded; not represented in Fig. 2 for clarity).

The influence of the distance heater-sample was investigating by keeping the same emitting temperature but moving the heaters from their initial position of distances between 20 and 50 mm. This is the same technique employed by Thomson and Drysdale [6] which leads to changes for $\dot{q}''_0$. The resulting differences in $\dot{q}''_\tau/\dot{q}''_0$

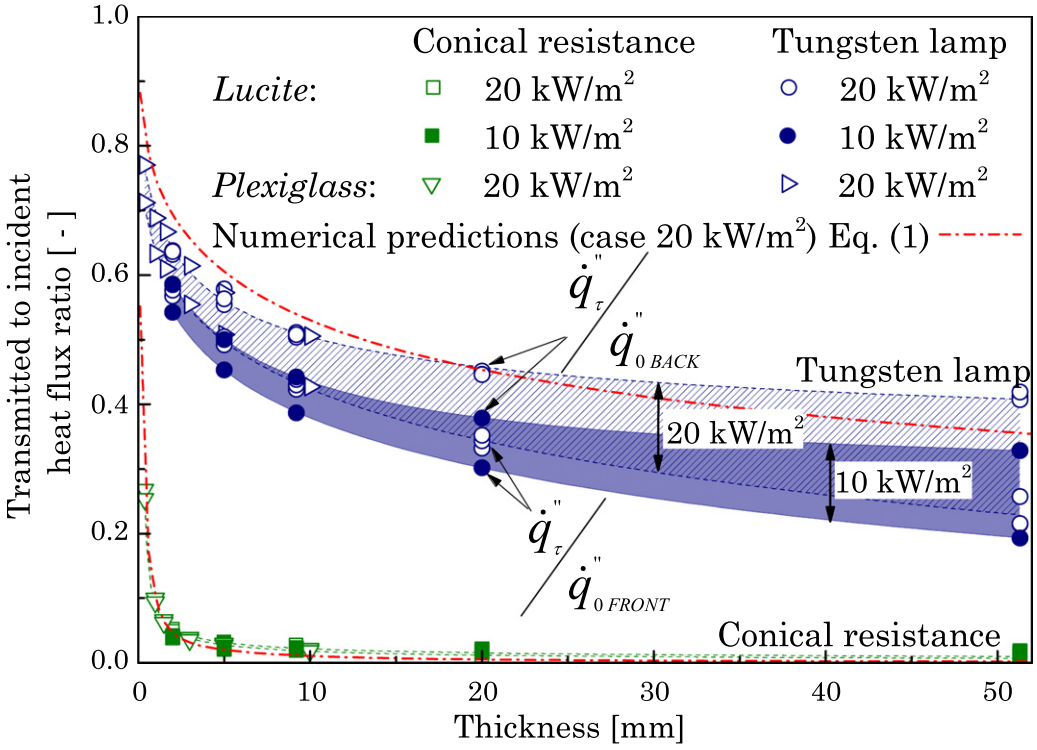

Fig. 2. Transmitted to incident heat flux ratio for clear PMMA samples (*Lucite* and *Plexiglass*) exposed to a radiative source (conical resistance and tungsten lamp) providing 10 and 20 kW/m^2 for thicknesses ranging between 0.375 and 51 mm.

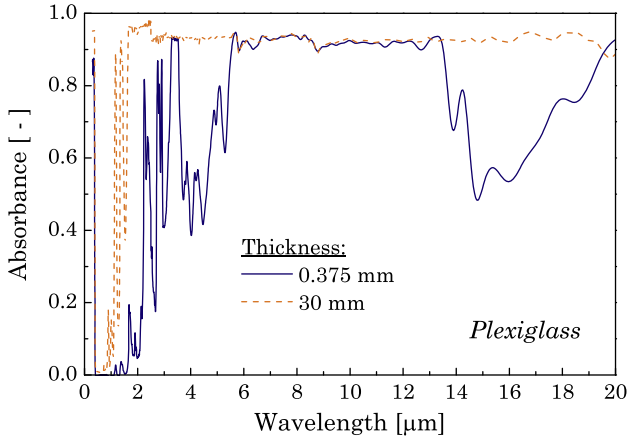

Fig. 3. Absorbance measurements for 0.375 mm and 30 mm thick *Plexiglass* samples.

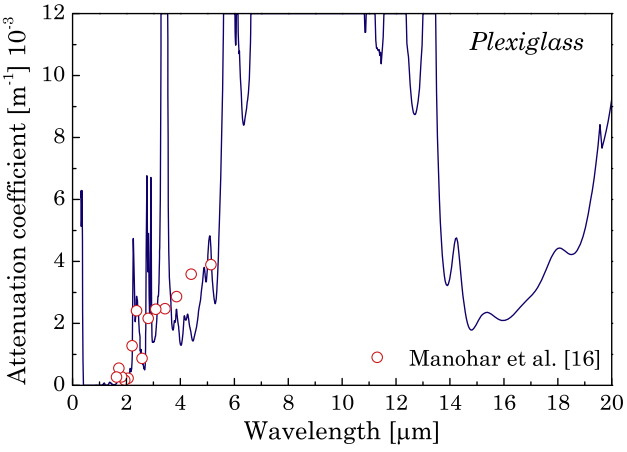

Fig. 4. Spectral distribution of the attenuation coefficient for *Plexiglass*.

measured for different distances heater-sample are lower than 5% (comparable to the repeatability error) and therefore the effect of distance on the ratio is considered negligible.

The sensitivity to the heater operating temperature was investigated by lowering the voltage to provide 10 kW/m^2 (at the original distance heater-sample). This change leads to lower operating temperatures of the sources. The 10 kW/m^2 level is reached with operating temperatures of 723 K for the resistance and 2248 K for the lamp, representing approximately a decrease of 15% from the operating temperatures at 20 kW/m^2. The resulting variation of $\dot{q}''_\tau/\dot{q}''_0$, shown in Fig. 2 (range represented by filled area), is significant for the lamp, whereas it is negligible for the resistance. This confirms the relatively low dependency of $\bar{\alpha}$ to operating temperatures measured by Försth and Roos [8] for clear PMMA samples of similar thickness (6 mm) using a resistance heater. However, the effect of the operating temperature depends on L and can be significant for thin samples.

In summary, measurements reported in Fig. 2 proof that radiative heat transfer through a sample depends strongly on thickness (or depth) and of the emitting source (type and operating temperature), but it is independent of the clear PMMA formulation and of the relative distance heater-sample. Both of these strong dependencies appear in Eq. (1) via α_λ which is function of the depth L, and via the spectral emitted intensity J_λ which depends on the operating temperature T and the source. These two variables are investigated simultaneously in the next sections whereas one of them was generally assumed in past studies.

3. Sample in-depth absorption

When a radiative beam crosses a gas–solid interface, a fraction r is reflected. The crossing part $(1-r)$ undergoes an exponential attenuation $e^{(-\kappa_\lambda L)}$ inside the solid according Beer–Lambert's law [11] (where κ_λ is the attenuation coefficient) up to the next interface where a fraction r of the remaining beam is reflected (see Fig. 1).

α_λ is the complement to the reflectance $\rho_\lambda(r)$ and the transmittance τ_λ (r) as pointed out in Eq. (2a). These quantities express respectively, the total reflected and transmitted components of the radiation resulting from multiple internal reflections [15].

$$\alpha_\lambda = \begin{cases} 1-\tau_\lambda(r)-\rho_\lambda(r) & \text{(a) multiple reflections} \\ 1-(1-r)^2 e^{(-\kappa_\lambda L)} - r & \text{(b) simple reflection} \end{cases} \quad (2)$$

The spectral distributions of α_λ was measured for eight *Plexiglass* samples of thicknesses ranging from 0.375 to 30 mm. Results are plotted in Fig. 3 for the thinnest and the thickest samples only. ρ_λ and τ_λ were measured using integrating spheres with a Perkin Elmer Lambda 900 double beams spectrometer in the wavelength interval [0.3–2.5 μm] and with a Bruker Tensor single beam spectrometer in the interval [2.5–20 μm]. Details on the procedure can be found elsewhere [8]. The repeatability of the measurements, based on three repeats, is good with a standard deviation lower than 3.5 10^{-3} on average over the wavelength interval [0.3–20 μm] and a maximum of 0.033.

The observed independency of $\dot{q}''_\tau/\dot{q}''_0$ on the type of clear PMMA reported in Fig. 2, is confirmed spectrally by the near perfect agreement of α_λ (not plotted - standard deviation lower than 4.5 10^{-3} in average) between *Plexiglass* and *Lucite* samples (cast and extruded).

The measurements of α_λ in Fig. 3 shows large heterogeneities over its spectral dimension (non-grey property) between 0 and the maximum $(1-\rho_\lambda)$. When L increases, a larger part of the irradiation is absorbed (as predicted by Beer–Lambert's law) and the width of the bands where α_λ is not maximum (visible and near-infrared bands) is reduced.

Using these measurements of α_λ, the spectral distribution of κ_λ has been calculated numerically by solving the 3rd order equation in $e^{(-\kappa_\lambda L)}$ resulting from multiple reflections (see [15] for details). The solution is most challenging for wavelength bands where the transmission is close to 0 or close to $(1-\rho_\lambda)$. Most of the problems of signal saturation (high transmission for visible and near-infrared bands) and of low signal-to-noise ratio (low transmission for infra-

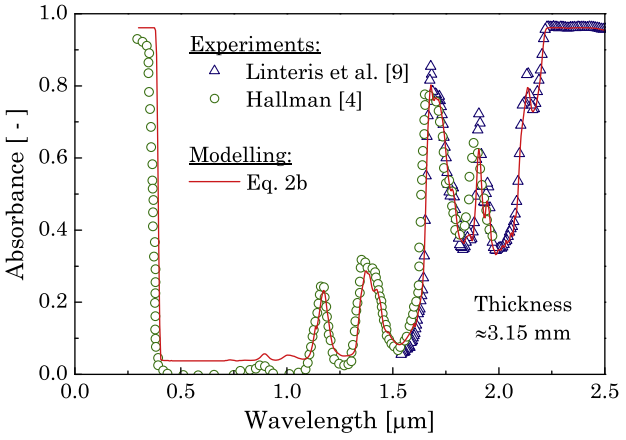

Fig. 5. Comparison of independent measurements of the absorbance with predictions based on the measured attenuation coefficient.

red bands) were avoided by using respectively, thick samples (L = 30 mm) to reduce the bands of high transmission and thin samples (L = 0.375 mm) to reduce the bands of low transmission. For the bands where the problem was still present, κ_λ was set to 0 m^{-1} for bands of high transmission and 12000 m^{-1} for bands of low transmission (best estimation for a reasonable signal-to-noise ratio).

Fig. 4 shows the obtained spectral distribution of κ_λ for *Plexiglass*. κ_λ is lower than 1000 m^{-1} only in the range [0.5–2.7 μm]. Given that κ_λ is the inverse of the mean penetration distance, almost the entire radiation spectrum of interest to fire science is absorbed in a thin layer lower than 1 mm from the top of the exposed surface. This is in agreement with the recent experimental observations from Linteris et al. [9]. The only measurements of κ_λ available in the literature are those of Manohar et al. [16] (symbols in Fig. 4) over the narrow band [1.59–5.56 μm]. These have been included in Fig. 4 to show that the agreement is good over the band although Manohar et al.'s [16] measurements carry a very large noise and only average values are presented.

Above 13.5 μm, the attenuation coefficient appears to decrease down to around 2000 m^{-1} meaning that the average penetration distance is above 0.5 mm. This behavior of the attenuation coefficient above 13.5 μm explains the decreases of absorbance observable on Fig. 3 for the sample of 0.375 mm.

Once κ_λ is known, it can be used to calculate α_λ for any sample thickness inside the studied range. When ρ_λ is not known, the multiple reflections need to be neglected and Eq. (2b) for a simple reflection should be used as first approximation (r is estimated from the refractive index taken as 1.49 for *Plexiglass* [15]). This calculation is used to predict in Fig. 5 the independent measurements of α_λ conducted by Hallman [4] and Linteris et al. [9] for L = 3.175 and 3.15 mm respectively. The good agreement observed between experiments and predictions shows the robustness of the measured κ_λ. It is expected that even more accurate calculations can be obtained with a good knowledge of ρ_λ. While the global reflectivity is theoretically dependent of the sample thickness due to the internal reflections [15] (see Fig. 1), the measurements of the reflectivity performed on the eight tested thicknesses (representative range for flammability tests) do not present significant variations (standard deviation lower than 10^{-10}). The smoothness of the samples can be considered therefore reasonably correct.

Knowledge of κ_λ serves to quantify the depth of the absorption but the magnitude absorbed depends on the spectral distribution of the radiation from the source. In the following section, the spectral intensity of the two sources is measured to complete the understanding of the sample-heater interaction.

4. Spectral emission from heaters

The two heaters used in this study (conical resistance and tungsten lamp) are different in multiple senses such as the physical principle, material, operating temperature, shape and distance to sample.

The spectral intensity J_λ of the heaters has been measured by comparing the emission received by a spectrophotometer from the heaters to that from a reference blackbody (Mikron M330 EU) at high temperature. The spectrometer (Vertex 80 V) is used with different detectors (DTGS and Si) and beamsplitters (Ge-KBr and CaF2 – function of the investigated range). The ranges of study are respectively [1.6–22 μm] for the conical resistance and [0.5–22 μm] for the lamp. Outside these ranges, the accuracy of the measurements would be low but the emission from the heaters is negligible as well. More details on the methodology can be found in Ref. [17]. The temperature of the heaters was set to 858 K and 2610 K, like for the broadband measurements reported in the second section. Each measurement has been repeated twice and the error is estimated lower than 5%.

Fig. 6 shows the measurements for the spectral distribution of J_λ. Significant differences are appreciable between both heaters. The resistance emits 90% of its intensity over the range

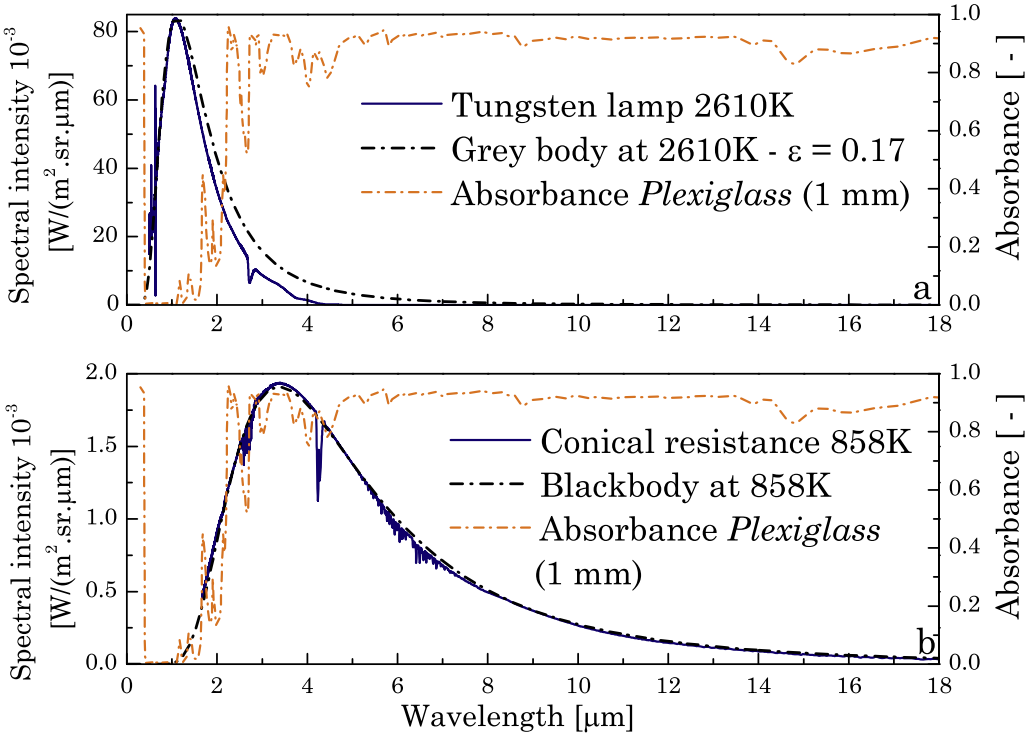

Fig. 6. Spectral distribution of the emitted intensity (left axes) for (a) the tungsten lamp at 2610 K and (b) the conical resistance at 858 K. The measured absorbance for a 1 mm *Plexiglass* sample is shown on the right axes for comparison.

[1.66–10.1 μm] with a peak at 3.40 μm. The lamp emits the same percentage on the narrower range, [0.5–2.8 μm], with its peak at 1.08 μm. The lamp's peak is more than 40 times higher in magnitude than the resistance's peak. Also, the measurements at different operating temperature (not represented) provide similar curves but the peak shifts to lower wavelength for higher temperature, as expected.

Fig. 6b shows that the calculated spectral intensity from a blackbody using Planck's law at 858 K matches near perfectly the experimental J_λ for the electric resistance. This demonstrates that the electric coils emit as blackbodies and validates this common assumption for this heater. The lamp, which emits strongly in the visible and the near-infrared (signal weak for $\lambda > 4.3$ μm), does not present a blackbody behavior. Fig. 6a also includes comparison to the intensity emitted by a greybody at 2610 K with an emissivity of 0.17 and allows concluding that the lamp spectral emission does not behave as a greybody either. It is believed that this non-greybody behavior is induced by the spectral emissivity of tungsten [11], but also by the bulbs, the window and the cooling system (water and air) of the lamp.

5. Discussion

The previous two sections provide fundamental insights which enable a better understanding of the radiative sample-heater interaction presented Fig. 2.

The measurement of κ_λ, which is shown here to be strongly heterogeneous for clear PMMA with variation from 0 to 12,000 m^{-1} (Fig. 4), allows understanding how α_λ varies with L (Fig. 5). This large heterogeneity is the reason why Linteris et al. [9] found $\bar{\kappa}$ (average of κ_λ obtained from broadband measurements) to be dependent of L instead of being an intensive property. An opaque material (no transmitted heat flux) does not absorb necessarily all the radiation close to the surface and the opacity criterion is dependent of the sample thickness. Only the spectral distribution of κ_λ or the broadband quantity $\dot{q}''_\tau/\dot{q}''_0$ for different thicknesses provide the necessary information on the absorbing depth. However, $\dot{q}''_\tau/\dot{q}''_0$ integrates the dependency associated with the heater and cannot be applied to other radiation scenarios.

Then, J_λ provides the magnitude of radiation received by the sample. In case of heaters behaving as a blackbody, such as the resistance, Planck's law provides the spectral variation of J_λ and the only additional required information is the heater operating temperature. If the heater can be considered as a greybody instead, the value of its emissivity is also required. In the other cases (heater neither black nor grey), like for the lamp in this study, a full characterization of J_λ is required.

The direct comparison in Fig. 6 of the measurements of α_λ(right axes) and J_λ(left axes) shows that the resistance emits the majority of its radiation in the wavelength band of maximum absorbance for a sample of 1 mm. It is the opposite case for the lamp which emits mainly in the low absorbance region meaning that only a small part of the radiation is actually absorbed by a sample 1 mm thick. This is confirmed Fig. 2 where the resistance transmits only around 10% of the incident heat flux for $L = 1$ mm while the lamp transmits between 63 and 69%. The numerical prediction of $\bar{\tau}$ using Eq. (1) with the measured values of κ_λ and J_λ is plotted in Fig. 2. The predictions agree well with the measurements of $\dot{q}''_\tau/\dot{q}''_0$ and capture the dependence with L and the heater type despite the assumptions made. The main assumptions(not necessarily justified) are that the heater and the sample are perfect diffusive surfaces, that the temperature distribution over the resistance coils and tungsten filaments is uniform, that radiation beams are collimated (i.e. the view factors of the source to the top surface is equal to the view factor of the source to the back surface) and that no other surface or medium exchange radiation. These assumptions, explain the relative small discrepancies in Fig. 2 between experimental measurements and numerical predictions. While the heaters are positioned normal to the sample, all the incident beams are not normal to the free surface. The influence of the incident angle, investigated using Fresnel equations, has not been included in Eq. (1) due to the negligible improvement when considered. Eq. (1) should be taken only as a qualitative tool with enough complexity to capture the main dependencies of the sample-heater interaction.

In this study, the heat flux received is only considered over a gage. Its surface is relatively small and the uniformity of the heat flux received over it can be reasonably assumed. The heaters and their positions in the flammability test apparatus have been designed (e.g. cone shaped instead of a plate) in order that the uniformity could be guarantee over typical sample surface area ($\approx$ 0.01 m^2). Nevertheless, this assumption needs to be verified in the experimental procedure [2,3].

Because radiation absorption is directly dependent of the sample-heater interaction, these results proof experimentally the necessity of a multi-band radiation model to calculate accurately the heat transfer to the free surface of a translucent fuel. Manohar et al. [16] and Sohn et al. [18] shown this numerically but only for a small spectral range [1.59–5.56 μm]. In fact, this will affect directly in-depth temperature profile and hence the pyrolysis process. The number of bands required would depend on the applications (e.g. thickness and heat source). For example, to predict the penetration depth within 1 mm accuracy, only the spectral distribution of κ_λ over the range [0.5–2.7 μm] ($\kappa_\lambda < 1000$ m^{-1}) is required.

The temperature profile of a fuel sample absorbing significant radiation inside the interval [0.5–2.7 μm] will be therefore significantly different from the temperature profile of a sample absorbing outside this interval. For the same amount of energy absorbed, the first sample has a thicker thermal layer but the local temperatures are lower, affecting significantly its pyrolysis behavior [12] and the time to ignition [4].

At high heat flux levels, radiative heat transfer becomes predominant over conduction [14,19,20] and the spectral distribution of κ_λ needs to be considered over a wider band.

Regarding the limitations of the findings, we note that the radiative properties have been measured for a short period of exposition such that the heat absorbed by the sample is negligible and the sample temperature remains close to ambient. The in-depth temperature gradient and bubbling phenomenon (typical of PMMA pyrolysis) are expected to affect these radiative properties and the sample-heater interaction. The gas phase could also influence this interaction by absorbing part of the incident radiation [21]. The evolution of the attenuation coefficient as a function of these phenomena should be investigated further as advanced in Ref. [8].

Due to the significant effects that J_λ can have on the pyrolysis results, the use of the electric resistance alone will not allow capturing correctly the radiative heat transfer since it is not a good representation of real fires (wildland [17], industrial facilities (liquid fuel) [4], common items [22]). On the other hand, the use of the lamp increases the complexity of flammability tests since experimentalist teams need to consider the difference in the heat absorbed by two fuels. The combined use of both the resistance and the lamp sources is therefore recommended. Moreover, while the tungsten lamp is a more complex spectral source, it offers other advantages over the resistance in flammability testing not related to radiation alone. For examples, the lamp prevents the pyrolysis gases from being in direct contact with a hot source possibly affecting the time to ignition and the absence of vertical obstacles just above the sample allows a better control of the flow field.

6. Conclusion

The sample-heater interaction for radiative heat transfer has been experimentally investigated for clear PMMA samples with two different heaters (electric resistance and tungsten lamp) commonly used in standard fire tests.

Broadband measurements of transmittance through samples of different thicknesses show that radiative heat transfer is strongly dependent on the heater type and operating temperature. For example, less than 10% of the incident heat flux is transmitted through a 1 mm thick clear PMMA sample when exposed to the electric resistance, whereas at 50 mm, a sample exposed to the lamp transmits more than 20% of the incident radiation.

However, clear PMMA formulation (*Lucite*/*Plexiglass*), manufacturing process (extruded/cast) and the relative distance heater-sample are shown to have a negligible influence on the transmittance.

The main dependencies observed on the broadband measurements were investigated more fundamentally through the quantification of the sample spectral absorbance and the spectral intensity emitted by the heater.

The attenuation coefficient, controlling the spectral absorbance through Beer–Lambert's law, has been estimated in this study for clear PMMA. It is the first time that this is performed over the full wavelength range encountered in real fires. The goodness of these calculations was shown by comparing the absorbance estimated from the attenuation coefficient to independent measurements in the literatures. The attenuation coefficient presents strong spectral heterogeneity (variation from 0 to 12000 m^{-1}). The assumption of a single effective value for this coefficient, as used nowadays in most of the pyrolysis model, cannot capture accurately in-depth absorption.

The spectral measurements of the emitted intensity by the heaters lead to three main conclusions. First, both heaters emit in significantly different wavelengths ranges. Second, the conical resistance behaves almost as a blackbody. Its spectral intensity can be described therefore by Planck's distribution and the operating temperature is the only required information. Third, the lamp does not even behave as a greybody and a full description of its spectral intensity is required. The blackbody assumption, usually accepted as first approximation is shown to not be always applicable.

Knowledge of the spectral distribution for these two fundamental variables (attenuation coefficient and emitted intensity) enables to understand better the radiative heat transfer to a translucent fuel. This investigation proofs the necessity of a multi-band radiation model to calculate accurately the heat transfer, which affects directly the in-depth temperature profile and hence the pyrolysis process.

However, the incident heat fluxes are generally assumed uniform and well collimated over the sample surface. These assumptions are strong and require more investigation in the future.

While the required complexity of the spectral heterogeneity for the attenuation coefficient is dependent of the application and the level of accuracy expected, radiative heat transfer is predominant in fire science and therefore the level of complexity used to predict it should be similar to the complexity of the others submodels such as the chemical degradation scheme.

Acknowledgements

The authors would like to thank S. Zhao (Uppsala University, Sweden), M. Krajcovic, F. Radford, I. Chang (University of Edinburgh, UK), P. Girods (University of Nancy, France) and H. Biteau (Exponent, USA) for their help and BRE Global and FM Global for their financial support.

References

[1] J.L. Torero, Flaming ignition of solid fuels, in: P.J. DiNenno et al. (Eds.), The SFPE handbook of fire protection engineering, 4th ed., National Fire Protection Association, 2008, pp. 2.260–2.278. ISBN-10:0877658218.
[2] ASTM E1354-10a: Standard test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter, ASTM International, West Conshohocken PA, 2010. <http://dx.doi.org/10.1520/E1354-10A>.
[3] ASTM E2058-03: Standard test method for measurement of synthetic polymer material flammability using a Fire Propagation Apparatus, ASTM International, West Conshohocken PA, 2003. <http://dx.doi.org/10.1520/E2058-03>.
[4] J.R. Hallman, Ignition characteristics of plastics and rubber, PhD thesis, The University of Oklahoma, Oklahoma, 1971.
[5] T. Kashiwagi, Effects of sample orientation on radiative ignition, Combustion and Flame 44 (1–3) (1982) 223–245. <http://dx.doi.org/10.1016/0010-2180(82)90075-X> .
[6] H.E. Thomson, D.D. Drysdale, Flammability of plastics I: Ignition temperatures, Fire and Materials 11 (4) (1987) 163–172. <http://dx.doi.org/10.1002/fam.810110402> .
[7] A. Tewarson, S.D. Ogden, Fire behaviour of polymethylmethacrylate, Combustion and Flame 89 (3–4) (1992) 237–259. <http://dx.doi.org/10.1016/0010-2180(92)90013-F> .
[8] M. Försth, A. Roos, Absorptivity and its dependence on heat source temperature and degree of thermal breakdown, Fire and Materials 35 (5) (2011) 285–301. <http://dx.doi.org/10.1002/fam.1053> .
[9] G. Linteris, M. Zammarano, B. Wilthan, L. Hanssen, Absorption and reflection of infrared radiation by polymers in fire-like environments, Fire and Materials, 2011. <http://dx.doi.org/10.1002/fam.1113>.
[10] R. Siegel, Net radiation method for enclosure systems involving partially transparent walls, NASA technical note, NASA TN D-7384, 1973.
[11] T.L. Bergman, A.S. Lavine, F.P. Incropera, D.P. Dewitt, Fundamentals of Heat and Mass Transfer, 7th ed., Wiley, 2011 (chapter 12, 768–860, ISBN-10:0470501979).
[12] P. Girods, N. Bal, H. Biteau, G. Rein, J.L. Torero, Comparison of pyrolysis behaviour results between the cone calorimeter and the fire propagation apparatus heat sources, Fire Safety Science 10 (2011) 889–901. <http://dx.doi.org/10.3801/IAFSS.FSS.10-889> .
[13] M. Chaos, M.M. Khan, N. Krishnamoorthy, J.L. De Ris, S.B. Dorofeev, Evaluation of optimization schemes and determination of solid fuel properties for CFD fire models using bench-scale pyrolysis tests, Proceedings of the Combustion Institute 33 (2011) 2599–2606. <http://dx.doi.org/10.1016/j.proci.2010.07.018> .
[14] N. Bal, G. Rein, Numerical investigation of the ignition delay time of a translucent solid at high radiant heat fluxes, Combustion and Flame 158 (6) (2011) 1109–1116. <http://dx.doi.org/10.1016/j.combustflame.2010.10.014> .
[15] P.T. Tsilingiris, Comparative evaluation of the infrared transmission of polymer films, Energy Conversion and Management 44 (18) (2003) 2839–2856. <http://dx.doi.org/10.1016/S0196-8904(03)00066-9> .
[16] S.S. Manohar, A.K. Kulkarni, S.T. Thynell, In-depth absorption of externally incident radiation in nongray media, Journal of Heat Transfer 117 (1) (1995) 146–152. <http://dx.doi.org/10.1115/1.2822295> .
[17] P. Boulet, G. Parent, Z. Acem, A. Kaiss, Y. Billaud, B. Porterie, Y. Pizzo, C. Picard, Experimental investigation of radiation emitted by optically thin to optically thick wildland flames, Journal of Combustion (2011). <http://dx.doi.org/10.1155/2011/137437> .
[18] Y. Sohn, S.W. Baek, T. Kashiwagi, Transient modeling of thermal degradation in non-charring solids, Combustion Science and Technology 145 (1–6) (1999) 83–108. <http://dx.doi.org/10.1080/00102209908924204> .
[19] T.J. Ohlemiller, M. Summerfield, Radiative ignition of polymeric materials in oxygen/nitrogen mixtures, Proceedings of the symposium (international) on combustion 13 (1) (1971) 1087–1094. <http://dx.doi.org/10.1016/S0082-0784(71)80106-6> .
[20] G. Linteris, Numerical simulations of polymer pyrolysis rate: effect of property variations, Fire and Material 35 (7) (2011) 463–480. <http://dx.doi.org/10.1002/fam.1066> .
[21] S.H. Park, A.J. Stretton, C.L. Tien, Infrared radiation properties of methyl methacrylate vapor, Combustion Science and Technology 62 (1988) 257–271. <http://dx.doi.org/10.1080/00102208808924012> .
[22] J.J. Comeford, The spectral distribution of radiant energy of a gas-fired radiant panel and some diffusion flames, Combustion and Flame 18 (1972) 125–132. <http://dx.doi.org/10.1016/S0010-2180(72)80233-5> .