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

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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):

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

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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.

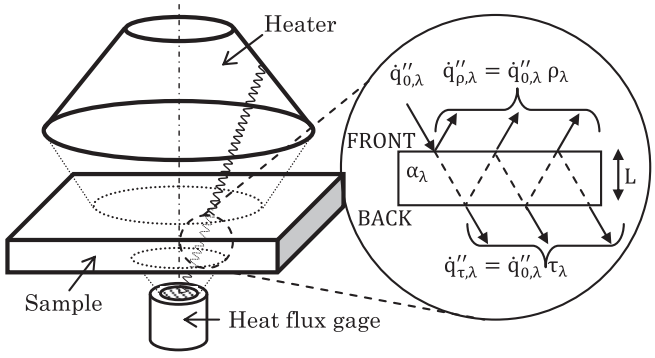

Fig. 1. Experimental set-up of the heat source, the sample and the heat flux meters. Insert: Schematic of the multiple reflection mechanism.

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.