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On the emission of radiation by flames and corresponding absorption by vegetation in forest fires

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ABSTRACT

Experimentations have been carried out in the infrared using Fourier transform infrared spectrometers. The obtained data characterize the emission of radiation by flames using vegetation as fuel. In a study conducted in parallel, the absorption of radiation by the vegetation has been investigated for several species. Usual assumptions of an emission equivalent to the one of a high temperature blackbody on the one hand, or of absorption close to the one of a black surface on the other hand, are discussed. Indeed, the emission by flames is strongly governed by hot gases produced by the combustion and the corresponding spectral emission is far from the one of a blackbody. In parallel, the spectral absorption of the vegetation varies with the wavelength, indicating a non-gray behavior. Fine descriptions should therefore involve a spectral modeling of radiation propagation, which is known to require huge computational costs. For simpler models aimed at producing approximate results but with a reduced computational effort, average values of absorptivities are suggested for two species (*Quercus coccifera* and *Pinus halepensis*) on the basis of the present results.

1. Introduction

In fire modeling, radiative transfer plays a key role as a propagating agent. Whatever the complexity of the propagation model which is developed, it has to include radiation effect as a source term in the energy balance. The actual contribution of radiation in the fire propagation of course depends on various factors: type of fire, geometrical considerations, wind conditions that will enhance the convection contribution and therefore decrease the relative role of radiation, etc…Works devoted to the simulation of the propagation all involve radiation, but with various refinement levels, however, (see [1–3] for example, among others). The difficulties commonly associated to radiative transfer are linked to the dependency of the intensity, which should be the fundamental function of interest when addressing radiative transfer, upon numerous variables, namely: position, time, but also propagation direction and wavelength or frequency of the radiation. Consequently one should start the study of radiation propagation whatever the application of interest, with a complete characterization of the radiation source, of the propagation medium and of the radiation absorber.

In the frame of forest fire, the problem is that there is still a lack of knowledge for the radiative properties, in terms of emissive power of the flames and absorption by the vegetation. A better evaluation of both aspects would help people interested in the propagation simulation. The present contribution is a synthesis of experimental works carried out by our group, focused on radiative transfer, in the frame of the PIF project devoted to the protection against forest fires and supported by the French National Research Agency (ANR). To our knowledge such a study, in particular involving a spectral analysis, is not yet available. One originality of the paper is that results and analysis will allow comparing absorption ability of plants, and emission characteristics of flames, in one single contribution. The basics regarding radiative properties involved in vegetation fire propagation are presented taking into account their spectral evolutions.

Flame emission has been already studied in the visible range, or with total radiation sensors. A spectral investigation in the infrared has been also conducted with spectrometers but this has been done on really small laboratory flames yielded by burners and using butane or propane as fuels [4]. The challenge here is to get information on flames produced by the vegetation at a larger scale and in outdoor conditions (closer to a real vegetation fire situation). Similarly, absorption by the vegetation has been also studied in the past, in the frame of remote sensing purpose for example, but this has been mainly done in the visible range or in the very near infrared range. Our goal is to extend the same experimental method to wavelengths relevant for fire propagation problems. A blackbody with a temperature around 1000 K

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would approximately emit 96% of its radiative energy in the wavelength range [1,45; 14,5 μm] (or in the corresponding frequency range [690; 6900 cm^{-1}], as it is often used in spectroscopy analysis). This would be the ideal range of interest for the present purpose. Actually, our measurements have been carried out in close ranges.

For the sake of the applicability of the present analysis, results have to be related to commonly used assumptions in fire propagation modeling: emission is often considered as coming from a blackbody at definite flame temperature, propagation from flame to vegetation is supposed to occur through a transparent medium, and absorption by the vegetation is assumed to be the one of a black surface, or a gray surface with high absorptivity. In order to check the validity of these assumptions, our work was devoted to

- the radiation emission by flames on the one hand,
- the absorption of the vegetation on the other hand,
- the combination of both set of data in a post processing step.

The experimental method lies on infrared spectroscopy using two Fourier transform infrared spectrometers and two types of detectors (HgCdTe and InSb types). Vegetation characterization has been done in our laboratory, whereas flame emission has been studied in outdoor conditions. Recent contributions [5,6] have been devoted to the presentation of the setups and some preliminary results. Therefore, the present paper will only include a short description of the experimentations and the post processing of the experimental data. The discussion will be focused on results of recent data acquisitions.

The paper is organized as follows: the second section is devoted to the emission of radiation by flames, the third section concerns the absorption by the vegetation and the computation of average properties taking into account the true emission of flames. The above cited common assumptions will then be discussed.

2. Characterization of the emission of radiation by flames

The measurement of radiation emission by flame has been conducted at various scales, as reported in [6]. Only laboratory tests of flames developed in a burning tray with a height around 50 cm are reported here. They have been conducted in outdoor conditions. The setup, which is presented in Fig. 1 through a schematic view and a picture of a typical flame, involves the following elements:

- a cylindrical burning tray with a diameter of 45 cm, and 10 cm deep, containing the fuel (dry vine branches and wood wool),
- a FTIR spectrometer: MATRIX type by Bruker which is a transportable spectrometer, chosen owing to its possible use in outdoor conditions, combined with a dual detector (HgCdTe and InSb) liquid nitrogen cooled,
- a reference emitter close to a blackbody at 1000 K located at the same distance from the spectrometer and used to provide a reference emission for the processing of the results (this robust emitter can be used without problem in outdoor conditions),
- a camera aimed at giving pictures in the visible range, of the flame observed in the infrared with the spectrometer.

Neighbouring surfaces have negligible influence on the emission characterization since the spectrometer is focused on a small area centered in the flame (approximately corresponding to a circle with diameter 6 cm at the position of the flame). No emission can be observed as a parasitic signal coming from the lateral wall aimed at avoiding some wind effect. Moreover, the wall on the rear plane is sufficiently far to avoid a significant increase of its temperature that would result in a superimposed emission pattern. This would produce an unexpected continuous emission and we will see in the coming analysis that such pattern is never seen when observing the flame emission.

Several tests have been conducted. Figs. 2(a)–(c) are typical spectra obtained for the spectral intensity emitted by flames produced by the combustion of wood wool and dry vine branches. Fig. 2(d) is a different test carried out with a line of sight coming from the burning vegetation area instead of the flame area solely, and will be discussed later in this section. Run 1 (Fig. 2(a)) is our basic case study, corresponding to the combustion of 0.2 kg (corresponding to 1.2 kg/m^2) of wood wool (*Excelsior*) and 0.5 kg (3.1 kg/m^2) of vine branches after reaching a near stationary flame, with measurements carried out in the flame, just above the burning vegetation. Numerous data acquisitions have been done, three are presented in order to illustrate the quite correct repeatability of the measurements (labeled runs 1.1, 1.2 and 1.3, respectively). Note that ignition was obtained without any addition of liquid fuel, only blowing air and using the hot embers of the preceding test. After this initial step of ignition, the flame was observed in quiet air (no wind). The combustion then lasts around 3 min with around 2 min of near constant flame (whereas the data acquisition is very fast, of the order of 0.1 s, therefore allowing several spectra to be registered and allowing to check the repeatability of the measurement process). Of course we observed that early and last stages of the flame development produced variable intensities but the repeatability was difficult to warrant and we preferred to restrict the analysis to the near stationary stage. As the flame is flickering some variations may appear in the intensity levels but the repeatability is quite good as can be confirmed by the spectra of Fig. 2. Data labeled Run 2 (Fig. 2(b)), again with three presented measurements labeled 2.1, 2.2 and 2.3, have been obtained in

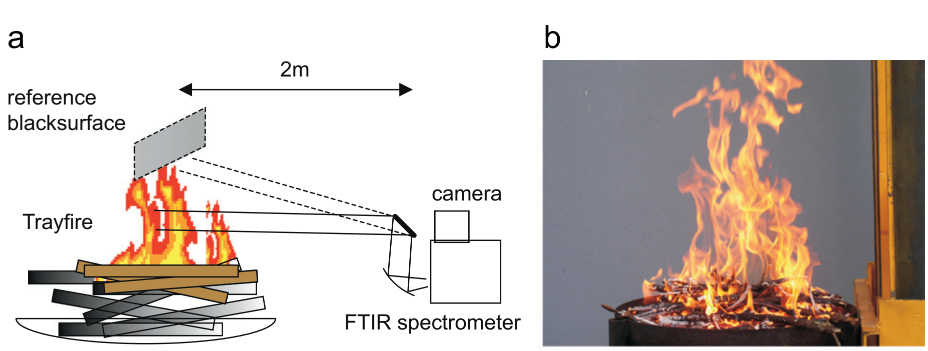

Fig. 1. Presentation of the device used for the flame emission study: (a) schematic view of the setup and (b) typical flame.

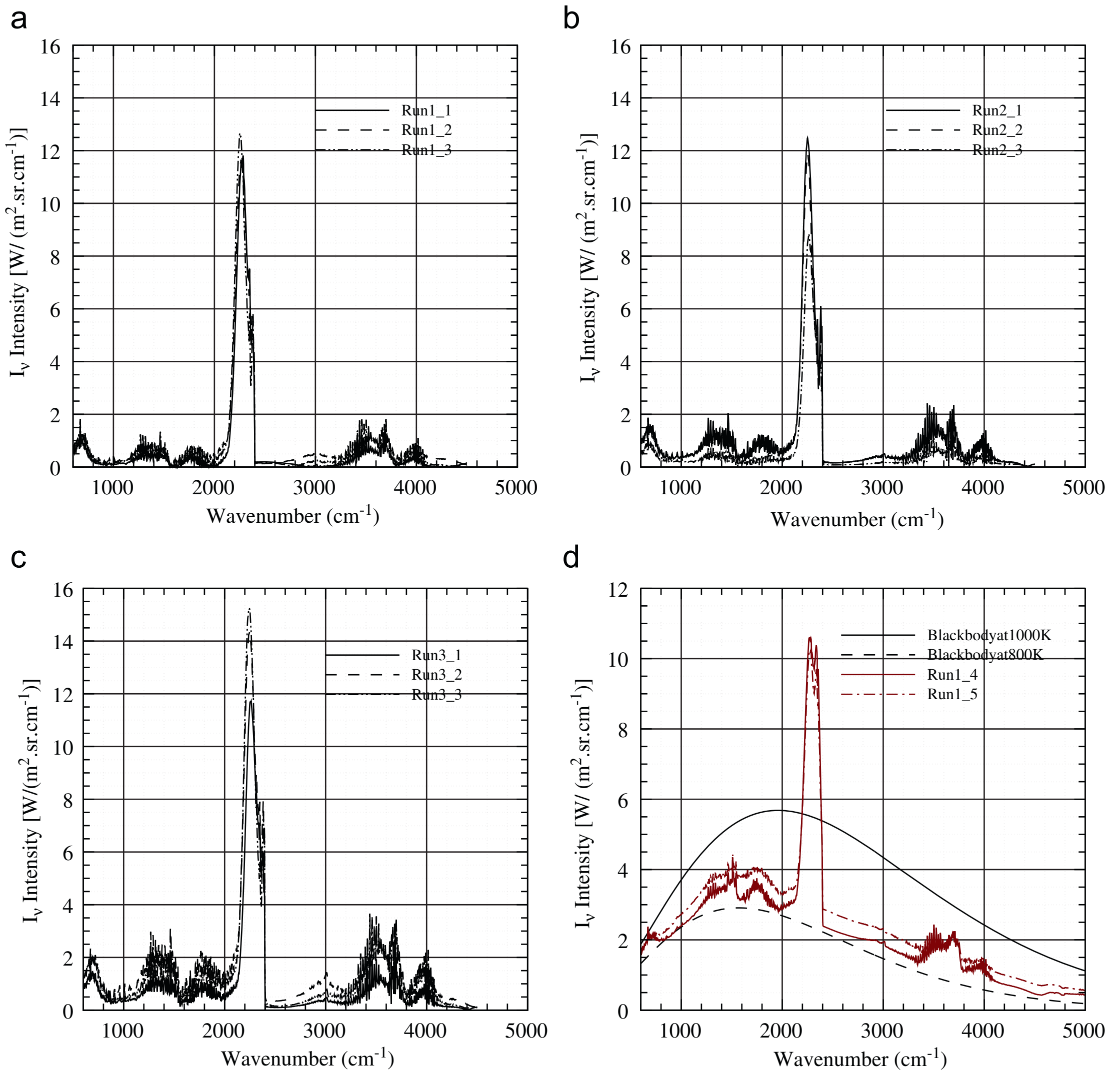

Fig. 2. Intensity emitted by the flame: (a) and (b) have been obtained for the same fuel load, at two different heights in the flame, (c) involves a double load of branches and (d) is the intensity measured when observing the burning vegetation area itself. Comparison with reference curves of blackbodies is presented in the same figure. (a) Emission just above the burning vegetation. (b) Emission in the top part of the flame: 40 cm above the burning vegetation. (c) Same as (a), double load of vine branches. (d) Intensity emitted by the embers and burning vegetation.

the same conditions but measuring the radiation emission 40 cm above the burning vegetation. Finally, measurements referred as 3.1, 3.2, 3.3 have been carried out in a third test (Fig. 2(c)), involving 0.2 kg of wood wool and 1 kg of vine branches (twice the previous load), just above the burning vegetation.

Results are given in terms of emitted intensity, obtained as follows:

$$I_\nu = \left(\frac{\phi_{\text{flame}}}{\phi_{\text{ref}}}\right)\left(\frac{\phi_{\text{ref}}}{\phi_{\text{bb}}}\right) I^\circ_\nu(T_{bb}) \tag{1}$$

where ϕ_x denotes a flux measured on one of the elements (flame or calibration device), and $I^\circ_\nu(T_{bb})$ is the blackbody intensity according to the Planck's law for a temperature T_{bb}.

This relation implies that a preliminary characterization of the reference emitter has been done investigating its behavior in comparison with a "true" blackbody (*HGH* type model 600 N). Respective measured fluxes are labeled ϕ_{ref} and ϕ_{bb}. Then, the measured flux emitted by the flame ϕ_{flame} is divided by the signal obtained in the same conditions with the reference emitter and multiplied by the blackbody intensity at T_{bb} (which allows to take into account the deviation of the reference emission from the one of a true blackbody). Data are only provided in the range 600–4500 cm^{-1} as signal outside was considered to be too weak to allow a serious analysis.

The most relevant features observed on all tests are:

- a strong peak between 2100 and 2400 cm^{-1}, which can be attributed to the CO_2, probably also to CO, produced by the combustion,
- important emission in the ranges [1000–2000 cm^{-1}] and [3500–4000 cm^{-1}], due to H_2O also produced by the combustion,
- no actual background emission as could be expected due to soot production, which indicates that at this scale the flame is not sufficiently thick or loaded in soots as to yield a large optical thickness.

Of course, combustion phenomena cannot be reduced to a simple production of CO_2, H_2O and soot, but the intensity is clearly observed in the frequency ranges associated to these two gases whereas only a weak emission is obtained in the intermediate range.

At this stage, we want to take these results with care and we avoid a real quantitative interpretation, as our main focus was an observation of the spectral behavior. Observing Figs. 2(a) and (b) one could think that the position in the flame (just above or 40 cm above the vegetation) has no actual influence on the emitted radiation, however, during some runs we observed a thicker flame in the bottom area and consequently a higher emission.

Fig. 2(d) presents really different results because this time, the line of sight is coming from the burning vegetation itself. The two emission curves have been obtained with the same load than for Fig. 2(a) (referred as run 1.4 and 1.5). As can be seen, the above mentioned peaks due to the gases are still visible, but there is a continuous background emission due to the hot and opaque surface corresponding to the vegetation. The emission level is really higher and can be compared to those of blackbodies at relatively high temperature, even if there is no information on the emissivity of the burning vegetation which is probably neither black, nor gray. A dedicated study could be carried out on that property analysis, simultaneously measuring the radiation emission and the temperature of this surface. In order to provide an indication on the emissive power, two curves corresponding to blackbodies at arbitrary temperature of 800 and 1000 K have been also plotted in Fig. 2(d). At this fire scale what we observe is that a really stronger emission can come from the burning vegetation itself and the embers, rather than from the flame solely.

In order to give an idea of the emissive power of the flame studied here, the integral over the frequency range of the spectrum can be computed, simply considering a total intensity as

$$I = \int_{\Delta\nu} I_\nu \, d\nu \tag{2}$$

where $\Delta\nu$ is the wavenumber range studied here: from 600 to 4500 cm^{-1}. For run 1.1, for example, a total intensity of 2.5 kW m^{-2} sr^{-1} has been found, which is a quite small value if we consider the possible high temperature of a flame. As a comparison, the same integral performed on run 1.4, on the intensity characteristic of the burning vegetation is 9.7 kW m^{-2} sr^{-1}. However, two reasons may explain this relatively weak power of the flame: (i) there is some attenuation due to participating gases along the optical path, (ii) the present flame is really optically thin at this laboratory scale, beside the emission due to the hot gases themselves. We want also to mention that the studied frequency range does not involve all the emitted radiation (as an example a blackbody at 1000 K would emit 13% of its radiative power outside the range [600–4500 cm^{-1}]). However, the emission by the flame is apparently not strong below 600 and above 4500 cm^{-1} when considering these limits in Fig. 2. Larger scale tests are now expected to provide more sooty and thicker flames, probably with a higher continuous emission level. Another important remark is that when observing the radiation emitted by a "fire", we do not consider the emission of the flame only, but what is coming from an area including flames, burning vegetation, hot ground, embers and so on. This must be taken into account in next radiative flux evaluations. The emitted flux seems higher when increasing the fuel load in Fig. 2(c) (which seems logical at first glance), but the increase is not really strong. Indeed, fine supplementary measurements will come in a next step in order to make a quantitative study, and check these first observations. What is obvious is that the present flame emission is really far from the one of a blackbody.

3. Absorption of radiation by the vegetation

Absorptivity of the vegetation is not measured directly but deduced from the measurement of directional hemispherical reflectivity and transmissivity in a second laboratory setup, which has been designed and presented in [5] for different vegetation elements (leaves or needles). It combines a FTIR spectrometer, an integrating sphere and an infrared detector, as presented in Fig. 3 and as described below:

- the FTIR spectrometer is an IFS66v/s apparatus by Bruker, with a beam splitter made of germanium on KBr,
- the source is a globar,
- the integrating sphere is specifically tailored to the infrared range with a gold internal coating referred as *infragold*,
- the detector is of HgCdTe type, liquid nitrogen cooled, by Kolmar technologies, working in a photovoltaic mode ensuring a good linearity.

The schematic view in Fig. 3(a), which corresponds to the picture in Fig. 3(b), indicates the optical path inside the spectrometer. Radiation is entering in the sphere and a part of radiation is reflected by the sample in this case, or transmitted if the sample is located between the spectrometer and the sphere. The signal is then collected by the detector.

The processing is based on these measurements of fluxes with the sample in transmission and reflection configuration (φ_t and φ_r), and a reference value φ_{ref} with the sphere in transmission configuration but without sample. The reflectivity of the sphere material in the wavelength range of use is taken into account (0.965 according to the manufacturer). A verification of the absence of parasitic signal has been also done with the sphere used in reflection configuration in the absence of the sample. This finally yields the following processing for the determination of the directional-hemispherical transmissivity (τ) and reflectivity (ρ) :

$$\tau = \frac{\varphi_t}{\varphi_{\mathrm{ref}}} \tag{3}$$

$$\rho = 0.965\,\frac{\varphi_r}{\varphi_{\mathrm{ref}}} \tag{4}$$

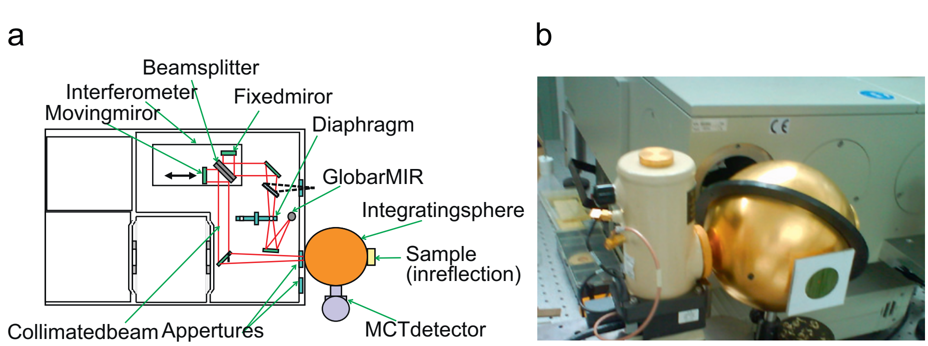

Fig. 3. Presentation of the device used for the study of reflection and transmission properties of the vegetation: (a) schematic view of the setup in reflection configuration and (b) picture of the setup.

Then the absorptivity is deduced from a simple energy balance:

$$\alpha = 1-\tau-\rho \tag{5}$$

The spectral range studied in this part is defined considering the bandwidth of the beam splitter, the sensitivity range of the detector and the signal level, finally leading to an analysis between 1000 and 7000 cm^{-1}. Results are presented here on two species with really different structures: *Quercus coccifera* and *Pinus halepensis*. Both are Mediterranean species currently involved in forest fires. For *Q. coccifera*, leaves have been placed across the incident optical beam with no particular difficulty, leading to transmission or reflection data depending on the position of the leaf with respect to the integrating sphere. Repeatability tests have been done indicating that present data on absorptivity can be taken with a confidence interval always better than $\pm 1.5\%$ in the whole range. Note also that measurements have been done on both sides of a given leaf showing that a discrepancy can be observed on reflectivity and transmissivity, but in a compensating manner so that the absorptivity remains unchanged, still in the same confidence interval. For *P. halepensis*, one single needle cannot be studied. A sample has been built by filling the area crossed by the incident beam (close to a circle with diameter 2 cm) with needles tightened side by side. This results in a kind of tissue with unavoidable interstitial holes unfortunately, that could induce an overestimation for the transmission and an underestimation for the reflection (as transmitted radiation would come partly from these holes and not after propagating through the vegetal matter, and on the contrary these void spaces would not produce the expected reflection of the matter). Therefore a threshold correction has been performed using information in the range where the vegetation is known to behave as an opaque body. In this range the corresponding transmission (τ_0) is an indication of the porosity of the built sample. The corrected transmissivity and reflectivity are then given by the following relations (see [5] for a complete description of the measurement process and the associated post-processing):

$$\tau_{cor} = \frac{\tau-\tau_0}{1-\tau_0} \tag{6}$$

$$\rho_{cor} = \frac{\rho}{1-\tau_0} \tag{7}$$

All data presented and discussed in the followings have been treated with this method (the subscript "cor" is no more repeated for the sake of brevity).

Figs. 4 and 5 give the spectral absorptivity of the two species. One can see that despite the fact that their structure is very different, they exhibit very similar variations. Note that the absorptivity is near constant for wavenumbers below 3700 cm^{-1} (or wavelengths above 2.7 μm). However, outside this range, the observed behavior is clearly non-gray and assumption mentioned in the introduction of vegetation behaving like a black or gray surface is clearly wrong.

Considering that computations cannot take into account all the complexity of the spectral characteristics because of the consecutive huge computational cost, one can search for what could be the average value for the radiative properties of the vegetation. The common method uses a Planck's mean considering a given incident radiation:

$$\langle \alpha \rangle = \frac{\int_{\Delta\nu} \alpha_\nu I_\nu \, d\nu}{\int_{\Delta\nu} I_\nu \, d\nu} \tag{8}$$

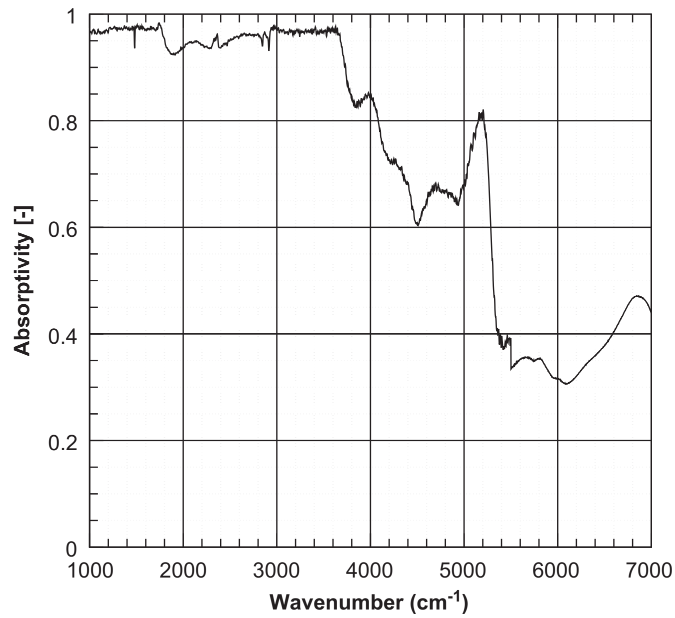

Fig. 4. Absorptivity of *Q. coccifera.*

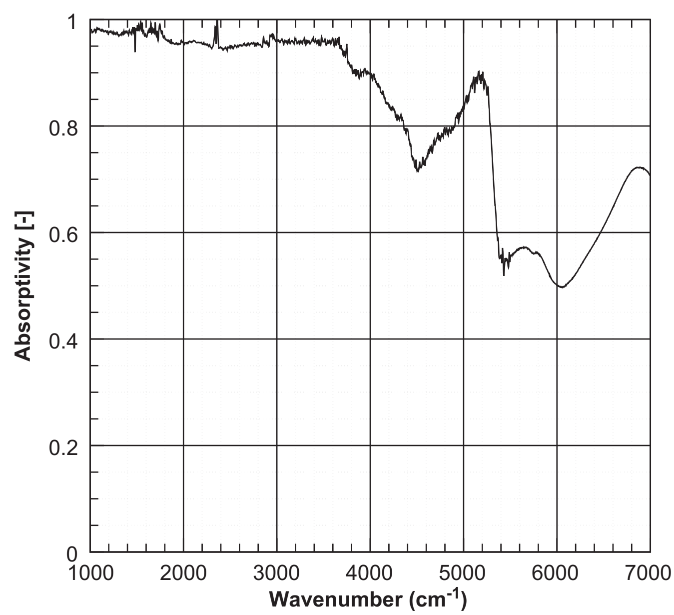

Fig. 5. Absorptivity of *P. halepensis.*

where $\langle \alpha \rangle$ is the averaged absorptivity based on the spectral data α_ν, and I_ν is the intensity received by the vegetation (a reference blackbody intensity or a characteristic value of a true flame emission).

In order to provide usable data, this work has been done using the data presented on Figs. 4 and 5, with the incident intensities coming from blackbodies at temperature 800 K or 1000 K. Comparison has been also carried out using the spectral emission provided on Fig. 1 instead of an hypothetic blackbody emission. Results are given in Table 1. Note that the absorptivity is not the only relevant parameter that characterizes the vegetation. For people modeling the radiative transfer through the solution of the so-called RTE (radiative transfer equation), the relevant property is the extinction coefficient or the absorption coefficient if the equivalent participating medium is assumed to be non-scattering.

Table 1
Average properties (α: absorptivity, ρ: reflectivity, τ: transmissivity) for *Q. coccifera* and *P. halepensis*.

	α	ρ	τ	$1-\tau$
Q. coccifera illuminated by				
Blackbody at 800 K	0.93	0.05	0.02	0.98
Blackbody at 1000 K	0.90	0.06	0.04	0.96
True emission in Fig. 1 (run1.1)	0.94	0.04	0.02	0.98
P. halepensis illuminated by				
Blackbody at 800 K	0.95	0.03	0.02	0.98
Blackbody at 1000 K	0.92	0.05	0.03	0.97
True emission in Fig. 1 (run1.1)	0.95	0.03	0.02	0.98

Vegetation under incident radiation with the spectral distribution of a blackbody or submitted to the spectral radiation given by Fig. 1 (run1.1).

The well known De Mestre's relationship provides a good prediction of the absorption coefficient, if leaves can be considered randomly distributed and oriented, and if the vegetation is assumed to behave like a black surface. In a previous contribution [5], authors have shown that it can be easily modified in order to take into account the deviation from the property of a black surface by simply multiplying the absorption coefficient by ($1-\tau=\alpha+\rho$) as follows:

$$\beta=(1-\tau)\cdot n_l\frac{S_t}{4} \tag{9}$$

with β for the extinction coefficient, n_l for the number density of leaves and with S_t designating the specific area of a vegetation element. τ stands for the transmissivity of the leaf (α and ρ for the absorptivity and reflectivity, respectively). All these properties are provided here as a synthesis of the present work, in order to give a set of useful data for the two presented species.

One can see that the absorptivity is in the range 0.90–0.95, with a little higher absorptivity for *P. halepensis*. The spectral evolution of the irradiation has an influence, as it was expected since radiative properties are varying with the wavenumber. It is confirmed by an averaged value which is slightly modified when changing the radiation source. Note that the use of a true emission (run 1.1) does not strongly change the obtained values despite this choice of an emission spectrum really far from the one of a blackbody. The integration considering the ember emission with its continuous spectrum would yield an intermediate and consequently very close results. Finally, if an extinction coefficient is sought, the correction factor ($1-\tau$) which is suggested as a multiplying factor for the De Mestre's relationship remains close to 1 (between 0.96 and 0.98 for the two species). These conclusions should help people searching for input data for their models when dealing with a simple modeling of radiative transfer. Of course, if a spectral treatment is chosen for the RTE solution, the curves presented here have clearly shown that properties are far from the commonly used assumptions of black emitters or absorbers. Several bands should be used in order to take into account the complex spectral variations.

4. Conclusion

Experimental results have been obtained in the infrared, using FTIR spectroscopy, for the spectral flux emitted by flames and the spectral absorption of two species: *Q. coccifera* and *P. halepensis*. The emission is clearly far from the one of a blackbody, since strong emission peaks or bands are observed due to the hot gases produced by the combustion, whereas a weak emission is observed out of these bands. In particular, no actual emission by soots has been observed but the laboratory scale used for the study could explain the fact that the flames were not optically thick. Results are different when observations concern radiation emitted by the burning vegetation or by the embers on the ground and higher emission levels are obtained indicating that the radiation is mainly coming from this area at this scale. Supplementary experiments are now required on larger flames and investigating all the radiation coming from the fire area, not restricted to the flame only. Concerning the absorption of the vegetation, a non-gray behavior has been observed. Average properties have been computed in order to provide realistic values for people involved in the propagation modeling who want to keep an efficient computation based on total properties instead of using complex spectral band models. Suggested values for the vegetation matter absorptivity are between 0.90 and 0.95, and correction factors for the computation of absorption coefficients (for example with the De Mestre's relationship) remain very close to 1 (0.96– 0.98).

Further works will be conducted with a systematic study of various species involved in forest fires. In situ measurements are needed. Emission by fires will be also studied on the same species and at various scales in order to involve higher optical thicknesses.

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