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# Experimental investigation on the heat fluxes generated by AP/HTPB solid propellant flames

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#### Abstract

This article describes an experimental investigation into the heat fluxes generated by the combustion of AP/HTPB solid propellant samples inside 1-MPa pressurized combustion chambers. Fluxmeters developed at ONERA and recently improved were used to measure the local heat flux densities. Two kind of fluxmeters were used: total fluxmeters for which the convective and the radiative components are measured and radiative fluxmeters for which the convective component is suppressed by the use of a sapphire window mounted on top of the fluxmeter. Additionally, the flame was visualized by a narrow-band filtered IR camera which provided quantitative and spatially resolved radiance field. From the IR camera recordings, a radiative heat flux equivalent to that measured by the radiative fluxmeters was constructed by means of the integration over the fluxmeters' collection volumes of the spectrally equivalent radiance. A satisfactory agreement is thus found between the two radiative heat flux measurement methods.

*Keywords:* Solid Rocket Motor, Solid propellant flame, Heat Flux, Fluxmeter, IR Radiation

#### 1. Introduction

The heat fluxes involved within the combustion chamber of a Solid Rocket Motor (SRM) are a key design aspect. The estimation of the heat flux levels is required to adjust the size and the material of the chamber's thermal protections

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[1, 2]. Heat exchanges also have a crucial impact on solid-propellant ignition [3]. More generally, radiative heat fluxes affect the propellant combustion rate by means of a feedback mechanism [4–6]. Good predictions of the heat transfers within SRMs - especially the radiative heat flux - are of importance for performance adjustments, ignition-system and structure designs.

Numerical simulation is a widely used tool for full-scale SRM design because of the difficulty of in situ experimental characterizations: SRMs are closed systems where hot-temperatures (> 2000 K) and high-pressure levels (> 5 MPa) are involved. Literature is extensive for numerical studies on plume radiation [7–11], which are of interest for detection safety issues. However, fewer studies are dedicated to the characterization of the heat fluxes within the combustion chamber [3, 12].

Radiation depends on several parameters including the presence (or not) of a condensed phase, i.e., aluminum particles and alumina residues. These induce various kinds of uncertainty for radiative calculations, e.g., uncertainty on the exact size distributions, which strongly depend on agglomeration phenomena on the solid-propellant surface [13, 14], uncertainty on the condensed-phase optical properties [3, 4, 15]. Hence, there is a need for extensive experimental characterization of the heat fluxes within SRM combustion chambers to support model developments and to provide confidence on numerical prediction.

Internal heat fluxes are, however, not easy to characterize. Experimental studies dedicated to the characterization of aluminum droplet combustion [16–18] mainly addressed the combustion phenomena rather than the radiative effect of aluminum droplets. Aluminum-droplet surface temperature was studied focusing on individual droplets [19] or larger populations [20]. In [20], the temperature dispersion obtained was large, showing the uncertainty of the measurement. Gases radiation of laminated samples were also characterized by means of an Infra-Red (IR) camera [21]. To our knowledge, no measurement has been performed to characterize both the convective and the radiative heat fluxes of a pressurized solidpropellant flame, with or without aluminum particles.

The present work aims at demonstrating a complete experimental approach to better characterize heat fluxes above a solid-propellant surface, both convective and radiative. Heat-flux sensors as well as an IR camera were employed.

For the past sixty years, ONERA has been developing and improving successive generations of surface temperature fluxmeters [22] to support the development of SRMs for the military and the space industries. They use the thin-film resistance thermometer approach, which was developed in the 1960s for shortduration heating phenomena associated to various kind of applications, e.g., unsteady flows, hypersonic flows, shock tubes [23–26]. These fluxmeters are of two kinds: total and radiative. The first sums up the convective and the radiative components of the heat flux, while the second isolates the radiative component by means of a sapphire window.

The measured radiative flux density is not a spatially-resolved quantity because it originates from the spatial integration of a radiance field contained in the collection volume of the fluxmeter. In order to provide better measurement of the radiative heat flux, the radiance field can be recorded by means of an IR camera. Spatial integration of this field over the collection domain of the radiative fluxmeter hence allows for comparison between the two measurement methods.

In the present article, small-sample combustion experiments performed in pressurized chambers are reported, for which both the fluxmeters and the IR camera were employed. In Section 2, the experimental set-up and the measurement techniques are described. The results are presented in Section 3. In Section 4, the analysis approach for comparing the measurements provided by the radiative fluxmeter to those originating from the IR camera is elaborated.

#### 2. Experimental set-ups and measurement techniques

#### 2.1. Combustion chambers

Two combustion chambers were used. The first one, here referred to as Chamber A, is a 472-mm long vertical tube with a 50-mm circular cross section. Figure 1 shows an overview of Chamber A. The chamber is closed at its bottom and top ends by means of flanges. The bottom flange is used to hold the solid-propellant sample. The sample is punched from a larger size solid-propellant block. Its dimensions are systematically measured prior being constrained to the sample-holder. Its faces, except the top one, are coated with an hydroxyl-terminated polybutadiene (HTPB) binder so as to inhibit lateral combustion and ensure a quasi-one-dimensional regression of the propellant surface. The composition used for the experiments reported in this article is an ONERA research composition made of 82% ammonium perchlorate (AP) oxidizer grain, 12.5% HTPB binder and non-metallic additives. The top flange is drilled to fit a window, by which a CO<sub>2</sub> laser beam (10.6  $\mu$ m wavelength) enters the combustion chamber for the purpose of igniting the sample. The laser pulse is set to a duration of 50 to 200 ms.

The external surface of the combustion chamber is designed to allow two sets of lateral flanges to be mounted opposite one another. Those flanges can either be (i) plain opaque walls, (ii) glass visualization windows or (iii) instrumented



Figure 1: Overview of Chamber A.

walls, each, with up to four fluxmeters housing positions. For the experimental campaign reported in the present article, two fluxmeter-instrumented flanges were used on one side of the chamber and six fluxmeters were employed in total (see  $\S2.2$ ). The labels of the fluxmeters are indicated in Figure 1. Details about the fluxmeters are given in  $\S2.2$ . The other flanges were plain opaque walls.

The chamber is not pre-emptied and is pressurized with nitrogen  $N_2$ , up to a pressure of about 10 bar, i.e., an initial  $N_2$  volume fraction of about 98%. The  $N_2$  intake before the onset of the combustion and the exhaust of the burnt gases afterwards are achieved by means of two connectors, respectively linked, to a compressed  $N_2$  tank and to the outside atmosphere. On both pneumatic lines, solenoid valves are actuated from pressure monitoring in the chamber.

Because the glass used for the windows of Chamber A does not transmit IR radiation, another set of experiments was performed with a second chamber equipped with  $CaF_2$  windows. This second chamber, here referred to as Chamber B, shown in Figure 2, is a 280-mm long and 55×55 mm<sup>2</sup> square cross section horizontal vessel.

Approximately half of the chamber consists of a visualization section where



Figure 2: Overview of Chamber B.

two 50-mm diameter  $CaF_2$  windows are facing each other. The visualization zone is centered on the solid-propellant sample whose holder - the same used for Chamber A - is mounted at the bottom of the chamber. Similarly to Chamber A, a flange is mounted at the top of the chamber and is equipped with a window for the ignition of the sample by the  $CO_2$  laser. Nitrogen intake and burnt gas exhaust are achieved by the same pneumatic lines as Chamber A. Chambers A and B have approximately the same volume.

#### 2.2. Surface temperature fluxmeters

The surface temperature fluxmeters, herein called fluxmeters, are of two kinds: total or radiative. Both are based on the theory of heat conduction in a semiinfinite homogeneous medium [22]. The physical principle behind these fluxmeters rests on the fact that the heat flux density at the surface of the sensor is related to the evolution of the surface temperature. This relation is obtained by means of a one-dimensional model that solves for the temperature profile in the wall with assumption of infinite depth. In practice, a total fluxmeter is composed of a fused silica  $(SiO_2)$  component, above which a thin platinum layer is sprayed (Figure 3). The fused silica component, i.e., the semi-infinite wall, ensures both the electrical and thermal insulations. The evaluation of the resistance of a constant electrical current flowing across the platinum layer (the sensitive element) directly leads to the determination of the surface temperature according to the relation:

$$\Delta T = \frac{R_0 - R}{aR_0} \tag{1}$$

with *R* the resistance of the platinum film,  $R_0$  its value at the reference temperature of 273.15 K and *a* the platinum temperature coefficient.



Figure 3: Schematics and photographs of the total (left) and radiative (right) fluxmeters.

The penetration length of the heat front into the fused silica, can be approximated by  $\sqrt{D_{th}t}$ , where t is the time, during which the heat flux is applied,  $D_{th}$  is the thermal diffusivity of the fused silica defined as  $D_{th} = \lambda/\rho c_p$ , and  $\lambda, \rho$  and  $c_p$ are, respectively, its thermal conductivity, density and specific heat capacity. For each samples of fused silica used by the fluxmeters, these thermo-physical properties where systematically measured, for which a mean value of  $D_{th} \approx 1 \text{ mm}^2/\text{s}$ is found. Thus, for the typical combustion time reported in this study  $t \approx 2 \text{ s}$ , a penetration length of approximately 1.5 mm is obtained. This is much smaller than the silica constituent's height (4 mm). We can then assert that the assumption of an infinite wall remains valid since the heat front does not reach the edge of the constituent.

The radiative fluxmeter is composed of a total fluxmeter, on top of which a 1-mm thick sapphire window is mounted (Figure 3). Hence, the convective

component of the total heat flux is suppressed by the sapphire window. Figure 4 shows its spectral transmittance  $\tau_s$ .



Figure 4: Spectral transmittance of the 1-mm thick sapphire window used by the radiative fluxmeters.

Thus, in practice, the determination of the convective heat flux density at a specific location can be determined as the difference between the total and radiative heat flux densities measured at the same location. In order to collect a larger portion of the radiative component, the platinum layer is coated with a black paint (Black-Velvet) of emissivity  $\varepsilon_{\text{paint}} = 0.95$  [27].

These fluxmeters can measure high transient surface temperatures with response times in the range of microseconds, values considerably smaller than the combustion duration. Their signals are sampled at a frequency of 20 kHz, digitally filtered by a low-pass filter of 40 Hz cut-off frequency and smoothed by a Savitzky–Golay filter of degree one and 25 ms window. Two configurations of six fluxmeters were used, three total (symbol ①) and three radiative (symbol  $\mathbb{R}$ ) housed at positions ① to ⑥ (see Figure 1). The configurations are from bottom to top : @@@@@@®@ for the first one (Cfg.1) and ⑦@@@@® for the second one (Cfg.2).

#### 2.3. Infrared camera visualizations

The flame radiance was recorded by means of a NOXANT Infra-Red (IR) camera equipped with an optical filter of Central Wave-Length (CWL)  $\lambda_{CWL}$  = 4017 nm. Figure 5 shows the measured and calculated spectral intensity in the plume of an AP/HTPB-based SRM adapted from Niu et al. [10]. The spectral transmittance of the optical system {filter+CaF<sub>2</sub> window},  $\tau_f \tau_w$ , is overlaid. The filter was thus chosen so as to avoid the large emission bands of CO, CO<sub>2</sub> and H<sub>2</sub>O and was centered about the HCl band. The depth of field of the camera is larger

than the chamber's width. Hence the intensity of a pixel measures the radiance integrated over the third direction.



Figure 5: Measured and calculated spectral radiant intensity of an AP/HTPB-based SRM exhaust plume (adapted from Niu et al. [10]). The spectral transmittance of the optical system {filter+CAF<sub>2</sub> window} is overlaid.

The camera recording was triggered 200 ms before the laser pulse and operated at a frame-rate of 300 Hz providing a 640 × 512 pixels image definition. The pixel dynamic range *I* was encoded on 13 bits, i.e., over 8192 Digital Levels (DL). Prior to the test, a grid was positioned inside the combustion chamber so as to evaluate the image magnification. The resolution of the image was thus evaluated at 122.1 ± 0.8 µm/pixel. The optical system, composed of the camera, the filter and the  $CaF_2$  window, was calibrated by means of a blackbody at settemperatures  $T_{BB}$  between 100 °C and 750 °C (±1 °C). The blackbody radiance  $L_{BB}$  is determined according to:

$$L_{\rm BB} = \int_{\lambda=0}^{\lambda=\infty} \tau_{\rm f}(\lambda) \tau_{\rm w}(\lambda) L_{\lambda}^{0}(T_{\rm BB}, \lambda) d\lambda$$
<sup>(2)</sup>

where  $L_{\lambda}^{0}$  is the Planck's law. The sensitivity of the optical system, i.e.,  $\alpha = L_{BB}/(I/\tau_{i})$ , with  $\tau_{i}$  the exposure time of the camera, is found to be linear ( $R^{2} = 0.999$ ). The uncertainty on  $\alpha$  is evaluated at  $\pm 3\%$ . Thereafter, the radiance *L* of the flame, in W/m<sup>2</sup>/sr, is deduced from the pixel intensity *I* according to  $L = (\alpha/\tau_{i}) I$ .

#### 3. Results

#### 3.1. Experimental conditions

Table 1 provides the experimental conditions of the cases reported in the study. All cases essentially consisted of reproductions of the same condition (pressure and sample size). Cases 1 and 2 realized with the configurations of fluxmeters Cfg.1 and Cfg.2 of Chamber A are complementary, to the extent that the total fluxmeters, and respectively the radiative fluxmeters, of Cfg.1 were replaced by radiative fluxmeters, and respectively, total fluxmeters in Cfg.2. Case 3 was obtained with Chamber B and recorded by means of the IR camera. Even though chambers A and B do not have the same geometry, from the radiation viewpoint, Case 3 is equivalent to cases 1 and 2. This case will hence serve as the basis for the radiative heat flux reconstruction detailed in Sect. 4, which will be compared to that of Case 1.

Case	Chamber	Config.	$P_0$ (MPa)	$D \times h (\text{mm})$
1	А	Cfg.1	1.08	$5.5 \times 7.4$
2	А	Cfg.2	1.05	$5.5 \times 7.4$
3	В	n/a	1.08	$5.4 \times 7.1$

Table 1: Experimental conditions of the cases reported,  $P_0$ : initial pressure in the chamber, D: sample diameter, h: sample height.

#### 3.2. Heat flux density measurements

Figure 6 shows the evolution of the heat flux densities measured by the total  $(\phi_t, \text{ left})$  and radiative  $(\phi_r, \text{ right})$  fluxmeters for cases 1 and 2. The laser pulse occurred at time t = 0.2 s, for which each plot shows a peak whose intensity decreases with the vertical position. This peak corresponds to the local heating of the gas by the laser pulse (duration < 70 ms). The radiative heat flux density rapidly drops along the *y*-axis as almost no signal is observed at axial positions  $y \ge 75$  mm (responsible). After the phase of laser-assisted combustion, radiative heat flux densities measured by fluxmeters (response) are linearly decreasing with time. This observation will be further analyzed in §3.3. Large amplitude fluctuations of the convective heat flux densities are also observed, which are resulting from the vortices created by the burnt gas flow leading to recirculations at the flame lateral borders.



Figure 6: Measurements of the total (left) and radiative (right) heat flux densities for cases 1 and 2.

#### 3.3. Flame radiance

Figure 7 shows the flame radiance measured by the IR camera at several times for Case 3. The (x = 0, y) and (x, y = 0) axes are, respectively, the symmetry axis of the sample-holder and the axis tangent to its surface. At time t = 0.23 s, contrarotative vortices created by the initial injection of burnt gas into the quiescent nitrogen are observed. Qualitatively, the turbulent aspect of the burnt gases flow at the flame borders explains the fluctuations of the convective heat flux densities observed in Figure 6.

Figure 8 shows the evolution of the radiance maximum  $L_{\text{max}}$ . At time  $t \approx 0.85$  s, the drop of the signal is attributed to the disappearance of the propellant surface, i.e., the highest intensity region, below the sample-holder plane, thus from the image.



Figure 7: Narrow-band filtered flame radiance measured by the IR camera at several times for Case 3. The time t = 0.2 s refers to the beginning of the laser pulse. The dynamic range is voluntarily truncated to ensure higher contrast of the images.

#### 4. Analysis

#### 4.1. Analysis approach

From the radiance field, the radiative heat flux density  $\phi_r^{\sim}$  integrated in a collection volume equivalent to that of a fluxmeter can be deduced and compared to the actual fluxmeter measurement  $\phi_r$  of Case 1 (see §3.2). It is defined as :

$$\phi_{\mathbf{r}}^{\sim} = \varepsilon_{\text{paint}} \int_{\Omega_{\mathbf{r}}} \int_{0}^{\infty} \tau_{\mathbf{s}}(\lambda) L_{\lambda}(\mathbf{u}) \, d\lambda \mathbf{u} \cdot \mathbf{n}_{P} d\Omega$$
(3)

where  $\varepsilon_{\text{paint}} = 0.95$  is the emissivity of the paint covering the platinum layer of a fluxmeter,  $\Omega_{\text{r}}$  is the collection domain of the fluxmeter,  $\tau_{\text{s}}$  is the spectral trans-



Figure 8: Evolution of the radiance maximum  $L_{\text{max}}$ .

mittance of the sapphire window,  $L_{\lambda}(\mathbf{u})$  is the spectral radiance of the flame. The vector  $\mathbf{u}$  defines the unit vector linking an infinitesimal surface of  $\Omega_{\rm r}$  and a surface element *P* of the fluxmeter (of normal  $\mathbf{n}_P$ ). The quantity  $d\Omega$  is the infinitesimal solid angle under which an element of  $\Omega_{\rm r}$  is observed from a fluxmeter. We define  $\theta$  as the angle between  $\mathbf{u}$  and  $\mathbf{n}_P$  so that  $\mathbf{u} \cdot \mathbf{n}_P = \cos \theta$ . In Eq. (3), the effect of multiple reflections in the sapphire window is assumed to be negligible.

The radiance integrated over the broader range of the sapphire window (see Figure 4), i.e., the quantity

$$L_{\text{broad}}\left(\mathbf{u}\right) = \int_{0}^{\infty} \tau_{s}(\lambda) L_{\lambda}\left(\mathbf{u}\right) d\lambda$$
(4)

constitutes the main unknown for which the following will focus on estimating.

#### 4.2. Condensed phase detection

The flame radiance comprises that of large diffuse clouds of spectrally active gaseous species (CO, CO<sub>2</sub>, H<sub>2</sub>O and HCl) as well as that of localized condensedphase hot spots. These are residuals of the pyrolysis of the HTPB used to coat the external surface of the sample. They have a typical flake-like shape. Figure 9 shows a magnification on one of these residuals and compares it to that captured by means of the focused shadowgraphy technique (developed at ONERA) and observed on the sample-holder after an experiment.

The extrapolation of the narrow-band radiance field  $L_{\text{narrow}}$  to the broad-band one  $L_{\text{broad}}$  relies on the knowledge of the spectral radiance from 400 nm to 7  $\mu$ m. Spectral radiances are different for the gas phase and the condensed phase above



Figure 9: Magnifications on HTPB pyrolysis residuals captured by means of the IR camera (top), focused shadowgraphy (center, unpublished results) and observed on the sample-holder after an experiment (bottom).

the solid-propellant sample. It is important to discriminate the two phases, i.e., automatically detect the condensed phase in all the images.

Condensed objects lead to small bright regions within the flame. However, their intensity levels strongly depend on the objects sizes and their positions within the gas flow. Using a single fixed threshold to segment the targeted regions is not an efficient approach, especially over a full test series with images displaying fluctuating intensity levels. The MSER (Maximally Stable Extremal Regions) algorithm [28] was chosen to detect the condensed-phase regions. It has been successfully used in the context of solid-propellant combustion, in particular, to characterize aluminum particles above the surface of burning propellants [29]. MSER uses adaptive thresholding in order to detect objects whose shape is maximally stable. The retained regions have a surface that does not vary significantly when changing the threshold over a certain range. Further tests were included here in order to eliminate ambiguous regions, e.g., homogeneous gas-phase regions that would be selected as stable regions. Detected regions of surface larger than 4 mm<sup>2</sup> were discarded since no condensed object is expected to be as large in the present burning conditions. An aspect ratio condition was also implemented to avoid detecting bright vertical flame structures.

The MSER-based detection was used to decompose the radiance field  $L_{narrow}$  into two components respectively associated with the gaseous and the condensed phases:  $L_{narrow} = L_{narrow}^{gas} + L_{narrow}^{cond}$ . Figure 10 illustrates the decomposition with close-up portions of the various radiance fields.



Figure 10: Decomposition of the radiance field  $L_{\text{narrow}}$ : (a) Total radiance  $L_{\text{narrow}}$ . (b) Condensedphase radiance  $L_{\text{narrow}}^{\text{cond.}}$ . (c) Gas-phase radiance  $L_{\text{narrow}}^{\text{gas}}$ .

The condensed-phase radiance  $L_{narrow}^{cond.}$  field was built from the MSER regions. The gas-phase radiance  $L_{narrow}^{gas}$  was obtained by removing the condensed-phase regions from the initial image and filling up the blanks portions with neighboring radiance values. These values were also subtracted from the condensed-phase radiance so as to remove the local gaseous emissions present in front of the solid particles. The condensed-phase field  $L_{narrow}^{cond.}$  does correspond to bright portions of the image: from 500 to 1500 W/m<sup>2</sup>/sr compared to the gas-phase radiance  $L_{narrow}^{gas}$ , which is below 300 W/m<sup>2</sup>/sr. However, condensed-phase regions only represent a small proportion of the flame region, which limits their impact on the final integrated radiance values (<15% of the total radiance).

#### 4.3. Narrow-band to broad-band transfer functions

It is first assumed that the flame radiance does not vary between the direction **u** and the normal direction of the camera  $\mathbf{n}_P$ . Under this assumption of partial isotropic radiance, the radiative heat flux calculation will later be facilitated. Secondly, in order to relate  $L_{\text{broad}}$  to the measured narrow-band radiance  $L_{\text{narrow}}$ , hence decomposed, transfer functions  $\Gamma$  and  $\Upsilon$  such that

$$L_{\text{broad}} = L_{\text{broad}}^{\text{gas}} + L_{\text{broad}}^{\text{cond.}} \simeq \Gamma\left(L_{\text{narrow}}^{\text{gas}}\right) + \Upsilon\left(L_{\text{narrow}}^{\text{cond.}}\right)$$
(5)

have to be found.

The gas-phase transfer function  $\Gamma$  is determined from a numerical simulation performed by the CEDRE® code developed at ONERA. CEDRE® is a multiphysics simulation code, designed to solve multi-phase, reactive flows [30]. It has been used for some years for both fundamental and applied applications [31] towards the aeronautics (e.g., gas turbine engines [32, 33]), the space (e.g., liquid and solid rocket engines [34, 35]) and defense (e.g., ramjet and scramjet engines [36, 37]) industries.

The case, not reported in the present article, considered a two-dimensional simplified version of Chamber A geometry, in which a single gas (mass fraction  $Y_g$ ) is injected into a 1-MPa N<sub>2</sub> atmosphere with a surface flow rate of  $\rho_p r_p$ , with  $\rho_p$  the density of the AP/HTPB solid propellant and  $r_p$  its regression velocity. Prior to this, a chemical equilibrium calculation was performed by means of the ON-ERA thermochemical code COPPELIA® so as to assess the injection temperature  $(T_0 = 2265 \text{ K})$  and the equivalent gas thermodynamic properties. The local mass fractions  $[Y_k]$  of each radiative species species  $(k = CO, CO_2, H_2O, HCI)$  were determined from the composition at equilibrium  $[Y_k^0]$ , such that  $Y_k = Y_k^0 Y_g$ . Hence, from the transport viewpoint, we consider that all the species diffuse at the same rate. The flow of burnt gases being turbulent, this assumption is considered to be realistic. Table 2 provides values of  $Y_k^0$  determined by COPPELIA®.

<b>Radiative species</b> k	CO	$\mathbf{CO}_2$	$H_2O$	HCl
Mass fraction $Y_k^0$	0.32	0.11	0.21	0.24

Table 2: Equilibrium compositions of the radiative species of the AP/HTPB solid propellant combustion.

For several points of the flow extracted from the numerical simulation solution, each associated with a set of temperature and mass fractions  $(T, [Y_k])$ , a series of 0D radiance calculations in the broad and narrow spectral bands were performed by means of the radiation solver ASTRE [38, 39] of CEDRE®. Radiance calculations are based on models adapted for CO, CO<sub>2</sub>, H<sub>2</sub>O and HCl species radiations at high pressure [3, 40] and an optical thickness representative of the flame in the transverse direction. In these calculations, the transmittance of the flame, due to the absorption of these gaseous species, is taken into account. The results then obtained were used to construct the gas-phase transfer function  $\Gamma$  such that:

$$\begin{cases}
L_{\text{broad}}^{\text{gas}} = \Gamma\left(L_{\text{narrow}}^{\text{gas}}\right) \\
L_{\text{broad}}^{\text{gas}}(T, [Y_k]) = \int_{0}^{\infty} \tau_s(\lambda) L_{\lambda}^{\text{gas}}(T, [Y_k], \lambda) d\lambda \\
L_{\text{narrow}}^{\text{gas}}(T, [Y_k]) = \int_{0}^{\infty} \tau_f(\lambda) \tau_w(\lambda) L_{\lambda}^{\text{gas}}(T, [Y_k], \lambda) d\lambda
\end{cases}$$
(6)

The gas-phase transfer function is suited for the range of conditions of temperature and concentration obtained in the chamber during the regression of the sample. It does not however include the effect of pressure. This could however be neglected as the increase in pressure does not exceed 12 % of the initial pressure.

The condensed-phase transfer function  $\Upsilon$  is obtained from a series of blackbody radiance calculations performed at temperatures *T* ranging from 300 to 2500 K:

$$L_{\text{broad}}^{\text{cond.}} = \Upsilon \left( L_{\text{narrow}}^{\text{cond.}} \right)$$

$$L_{\text{broad}}^{\text{cond.}}(T) = \int_{0}^{\infty} \tau_{s}(\lambda) L_{\lambda}^{0}(T, \lambda) d\lambda$$

$$L_{\text{narrow}}^{\text{cond.}}(T) = \int_{0}^{\infty} \tau_{f}(\lambda) \tau_{w}(\lambda) L_{\lambda}^{0}(T, \lambda) d\lambda$$
(7)

The emissivity of the residuals is assumed to be constant over the spectral band of the sapphire so that it can be neglected in the rest of the calculations.

Figure 11 shows the functions  $\Gamma$  and  $\Upsilon$  thus obtained. These functions are strictly monotonic and are fitted with polynomial functions of degree 2 and R-squared values of 0.999.



Figure 11: Transfer functions  $\Gamma$  and  $\Upsilon$  for the determination of the equivalent radiance in the spectral band of the fluxmeters.

#### 4.4. Radiance integration

Finally, Eq (3) rewrites as:

$$\phi_{r}^{\sim} = \varepsilon_{\text{paint}} \int_{\Omega_{r}} L_{\text{broad}} \cos \theta d\Omega$$
  
$$= \varepsilon_{\text{paint}} \int_{\Omega_{r}} \left[ L_{\text{broad}}^{\text{gas}} + L_{\text{broad}}^{\text{cond.}} \right] \cos \theta d\Omega$$
  
$$= \varepsilon_{\text{paint}} \int_{\Omega_{r}} \left[ \Gamma \left( L_{\text{narrow}}^{\text{gas}} \right) + \Upsilon \left( L_{\text{narrow}}^{\text{cond.}} \right) \right] \cos \theta d\Omega$$
(8)

Since the fluxmeter's sensitive element is withdrawn from the surface of the window (see Figure 3), the collection domain is not the half-space facing the fluxmeter  $(2\pi \text{ sr solid angle})$ , but a cone of angle evaluated at 77°. In two dimensions, the domain  $\Omega_r$  is thus the intersection of this cone and the z = 0 plane, as illustrated in Figure 12 for the (a) fluxmeter.



Figure 12: (a) Illustration of the collection cone of the radiative fluxmeter  $\mathbb{Q}$ . (b) Illustration of the radiance integration into a radiative heat flux. (c) Domains  $\Omega_r$  of the radiative fluxmeters  $\mathbb{Q}$ ,  $\mathbb{Q}$  and  $\mathbb{Q}$ .

In practice, the integration of the radiance into a radiative heat flux density is obtained by summing up the contributions of each pixel of coordinates (i, j)

(Figure 12), which are assumed to originate from the single z = 0 plane. This assumption is justified since the depth of the flame is approximately ten times smaller than the mean distance between a flame element and a fluxmeter. Equation (8) hence approximates to:

$$\phi_{\rm r}^{\sim} \simeq \varepsilon_{\rm paint} \sum_{i,j\in\Omega_{\rm r}} \left[ \Gamma\left(L_{i,j}^{\rm gas}\right) + \Upsilon\left(L_{i,j}^{\rm cond.}\right) \right] \cos\theta_{i,j} d\Omega_{i,j} \tag{9}$$

where  $L_{i,j}^{\text{gas}}$  and  $L_{i,j}^{\text{cond.}}$  are, respectively, the gas and condensed phase radiances associated with the (i, j) pixel. The element of solid angle  $d\Omega_{i,j}$ , under which the pixel is seen from the center of the fluxmeter, is defined as:

$$d\Omega_{i,j} = \frac{dS_{i,j}\mathbf{u}_{i,j} \cdot \mathbf{n}_{i,j}}{d_{i,j}^2} = \frac{dS_{i,j}\cos\theta_{i,j}}{d_{i,j}^2}$$
(10)

where  $dS_{i,j}$  is the pixel area of normal  $\mathbf{n}_{i,j}$  and  $d_{i,j}$  is the distance between the pixel and the fluxmeter midpoint *P*. Finally, substituting Eq (10) into Eq (9) yields:

$$\phi_{\mathbf{r}}^{\sim} \simeq \varepsilon_{\text{paint}} \sum_{i,j \in \Omega_{\mathbf{r}}} \left[ \Gamma \left( L_{i,j}^{\text{gas}} \right) + \Upsilon \left( L_{i,j}^{\text{cond.}} \right) \right] \frac{dS_{i,j} \cos^2 \theta_{i,j}}{d_{i,j}^2}$$
(11)

Figure 13 compares, at positions (a) and (b), the radiative heat flux density  $\phi_{\tilde{r}}$  hence constructed from the IR camera-recorded radiance (Case 3) to those actually measured by the fluxmeters  $\phi_r$  (Case 1, see §3.2). An overall good agreement is observed between the two characterization methods. Initially,  $\phi_r$  is approximately 10% higher than  $\phi_{\tilde{r}}$ . The ratio of the radiative heat flux density at position (b) to that at position (c) is approximately the same for both methods.

Nevertheless,  $\phi_r$  decreases over time whereas  $\phi_r^{\sim}$  remains approximately constant. One possible interpretation is that the sapphire window is slightly withdrawn from the edge of the fluxmeter (see Figure 3), so that a layer of solid particles, probably HTPB residuals, progressively builds up at the window surface, which in turns, reduces the amount of radiation collected.

The method of integration being hereby validated, the total radiative heat flux  $\phi_{\text{wall}}$  incident to the wall is determined by following the same procedure, but for the total radiance  $L_{\infty}$  of the flame, i.e., integrated between  $\lambda = 0$  and  $\lambda \to \infty$ . The spatial integration is here performed over the half-space domain  $\Omega_{1/2}$  facing the wall:

$$\phi_{\text{wall}} = \int_{\Omega_{1/2}} \int_{0}^{\infty} L_{\lambda} d\lambda \cos \theta d\Omega = \int_{\Omega_{1/2}} L_{\infty} \cos \theta d\Omega$$
(12)



Figure 13: Comparisons of the radiative heat flux density constructed from the IR camera-recorded radiance  $\phi_{r}^{\sim}$  to that actually measured by the fluxmeters  $\phi_{r}$  at positions (i) and (ii).

New transfer functions  $\Gamma_{\infty}$  and  $\Upsilon_{\infty}$  are defined to account for the total radiance, so that:  $L_{\infty} \simeq \Gamma_{\infty} (L_{narrow}^{gas}) + \Upsilon_{\infty} (L_{narrow}^{cond.})$ . Figure 14 shows the field of  $\phi_{wall}$  hence obtained at time t = 0.60 s. At position (a) (x = 0, y = 19 mm), a radiative heat flux density of ~ 13 kW/m<sup>2</sup> is obtained, which is approximately twice the value measured by the radiative flux meter. This difference accounts for the smaller collection volume of the flux meter and the spectral transmittance of the sapphire, which reduce the amount of flux collected.



Figure 14: Left: Narrow-band filtered radiance at time t = 0.60 s. Right: corresponding wall radiative heat flux density  $\phi_{wall}$ .

#### 5. Discussion and conclusions

In this work, an experimental investigation into the heat fluxes generated by solid propellant flames was presented. The combustion of samples of AP/HTPB composition inside a 1-MPa nitrogen pressurized combustion chamber was measured by means of (i) surface temperature fluxmeters mounted on the combustion chamber's wall, which provided the local levels of heat fluxes (total and radiative) and (ii) a narrow-band filtered IR camera.

The measurements provided by the radiative fluxmeters were compared to those of the IR camera. To do so, the camera-recorded radiance was decomposed into the contributions of the gases radiations and of the HTPB pyrolysis residuals by means of the MSER detection method. Then, transfer functions, which correlate the radiance in the spectral band of the IR filter to that of the sapphire, were determined for the gas-phase component and for the condensed-phase component. A spectrally equivalent radiative heat flux density was hence constructed by means of an integration of the radiance in the collection volume of the fluxmeter. A reasonable good agreement was thus found between the two radiative heat flux characterization methods. However, this agreement is based on several assumption (thin flame, partial isotropic radiance, ...) that we have considered to perform the computation. More experimental work is necessary in order to adjust the impacts of these assumptions: (i) study larger propellant sample diameters or (ii) reduce the collection volume of the fluxmeter.

The IR-camera radiance constitutes a two-dimensional (integrated over the third direction) resolved data, which should contribute to the improvement of the quality of the data used for the validation of the numerical simulations of solid propellant combustion. The special consideration given to the separation of the gas-phase and the condensed-phase radiations might seem excessive considering that, on average, the condensed-phase contribution does not exceed 15% of the total radiance. Nevertheless, this will prove useful in future works, in which aluminized solid propellants whose condensed-phase is much more radiative, will be studied.

The narrow-band filter used in this study avoids the bands of high emission associated with CO,  $CO_2$  and  $H_2O$ . It was chosen so as to avoid saturation of the IR camera which was used at a minimal exposure. Even though the transfer functions, appears to provide satisfactory results, it would be valuable, for a validation purpose, to use the IR camera recording collected in a spectral range that includes high emission bands, e.g that of  $CO_2$  around 4.4 µm. The saturation of the signal could be avoided by means of a density filter.

The total radiative heat flux that is emitted back to the solid propellant surface is of interest because of its impact on the solid propellant combustion [4–6]. However, the methodology of radiance-based radiative heat flux integration described in this work could not be directly applied to this case because it relies on measurements and transfer functions in the transverse direction of the flame. As the flame transmittance is not the same between the transverse and axial directions, radiative heat feedback on the propellant surface can not be deduced accurately with our results. Nevertheless, these results could be used to support and validate radiative numerical tools, which could, in a future work, be employed to determine radiative transfer in propellant flames including heat feedback.

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