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Analysis of combustion reaction based on infrared multispectral imaging

Abstract

Combustion analysis was carried out using Telops MS-IR MW camera which allows multispectral imaging at a high frame rate. A motorized filter wheel allowing synchronized acquisitions on eight (8) different channels was used to provide time-resolved multispectral imaging of combustion products of a candle in which black powder has been burnt to create a burst (carbon dioxide and water). It was then possible to estimate the temperature of the candle's plume by modeling spectral profile derived from information obtained with the different spectral filters. Comparison with temperatures obtained using conventional broadband imaging illustrates the benefits of time-resolved multispectral imaging for the characterization of combustion processes.

Keywords: multispectral detection, combustion analysis.

1. Introduction

One of the simplest combustion systems is a candle, which has brought lots of information on combustion process over the years [1]. Candle's waxes are mainly composed of long hydrocarbon chains (paraffin) which vaporize and combust when the molten wax reaches the flame by capillarity through the wick. Combustion is an exothermic process so it releases heat after combination of oxygen and combustible such as fuel. Complete combustion of paraffin leads to the production of water (H_2O) and carbon dioxide (CO_2) as shown in Eq. (1). Incomplete combustions typically lead to carbon monoxide (CO) in addition to unburnt reactants and/or soot ($C_{(s)}$). When the reactants contain elements such as sulfur or chloride, other combustion by-products such as sulfur dioxide (SO_2) and hydrogen chloride (HCl) can be found. At high temperatures, NO_x can also be produced due to the oxidation of nitrogen in the air.

$$C_nH_y + O_{2(excess)} \rightarrow nCO_2 + (y/2)H_2O \tag{1}$$

However, it is well known that absorption and emission of infrared radiation varies as a function of wavelength for most combustion gases. This absorption patterns refers to the infrared spectral signature. Such spectral features result from molecular vibrations energy transitions which are very unique to each chemical. By using broadband imaging systems, it is thus obvious that it becomes difficult when facing selective absorbers/emitters. Moreover, it is particularly challenging, or even impossible, to distinguish more than one infrared-active combustion gas without spectral information. Multispectral (MS) imaging allows to get spectral information and this is obtained by tuning the detector's spectral response using spectral filters such as band-pass (BP), low-pass (LP) and high-pass (HP). Filters can be cold (i.e permanent) or interchangeable at ambient temperature. No matter the configuration, the spectral range of the filter added in the optical path needs to be chosen carefully, since no filter change can be done without stopping the acquisition and/or redoing a radiometric calibration. Filter wheel systems are of interest since they allow to store a selection of spectral filters readily available for acquisition. The data is usually processed using ratios subtractions and/or combinations of multiple filters. The more different spectral filters are found in a wheel, the more flexibility is provided for the analysis of challenging situations. When spectral information is required, multispectral imaging may be a good compromise between the broadband imaging and the hyperspectral imaging. The latter although providing a full spectrum of every pixel, is less affordable than multispectral cameras which provide at least a few spectral features.

Combustion are phenomena that occur quickly, which means they require a good temporal resolution to be monitored. The best manner to provide such a high temporal resolution consists to equip the camera with a motorized filter wheel which allows fast rotation; otherwise the acquisition rate is too low and/or requires handling to select and/or change the filter. The Telops MS-IR infrared camera series allows dynamic multispectral imaging with a high frame rate thanks to a fast rotating filter wheel which includes eight (8) different channels. In order to perform time-resolved multispectral imaging, the filter wheel is driven synchronously with the FPA clocking such that a single frame is recorded at each filter position. All frames of a sequence are then calibrated using the in-band radiance (IBR) format according to their respective spectral filter. Due to its time-resolved capabilities and its spectral information, the MS system from Telops is particularly appropriated to follow a combustion process. Such a system has already been used previously in order to characterize vapour gas and minerals in the LWIR [2]. The experiments presented here will show the combustion of a candle in order to visualize how MS imaging is a powerful tool for monitoring combustion activities. Moreover, a sudden burst was generated by burning black powder in the candle flame which was easily monitored due to the good temporal resolution granted by the Telops MS system. The temperature profile of the plume has then been evaluated for the whole sequence.

2. Experiment setup and theoretical analysis

Telops MS-IR imaging systems (Fig. 1) are high performance cooled multispectral infrared cameras available in different models covering the complete mid-infrared spectral range. The MS-IR MW (3 – 5 µm) and MS-IR VLW (7.7 – 11.8 µm) use 640×512 pixels InSb (indium antimonide) or MCT (mercury cadmium telluride). All the MS-IR infrared cameras allow splitting of the scene radiance into eight (8) different spectral bands rather than only one broadband image hereby providing spectral information about the investigated targets. The filter wheel is a fast rotating mechanism designed to maximize the camera's frame rate and can be used either in fixed or rotating mode. The filter wheel is capable of reaching up to 6000 rpm, leading to a maximum effective frame rate of 800 Hz for the MS-IR-FAST, i.e. 100 Hz per channel. All cameras from the MS-IR series used in static mode benefit from the real-time radiometric temperature and non-uniformity correction features using Telops blackbody free correction method [3].

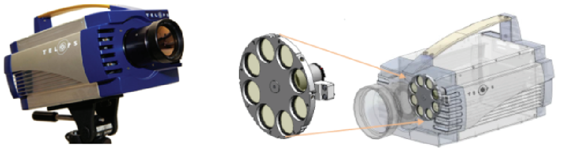

Fig. 1. Multispectral infrared camera (Telops MS-IR camera) (left) and filter wheel system (right)

The camera used for the experiment is a MS-IR MW in which cold filters were added in order to provide a spectral range covering between 3.7 to 4.95 µm. The transmittance curves of the different spectral filters used for this experiment are shown in Fig. 2. For the acquisition, full FPA frames were used (640×512) and the integration time was fixed between 12 and 800 µs depending on the filter. The integration time was chosen in order to avoid the saturation of the plume. Camera's frame rate was set to 100 Hz, which gives a frame rate of 12.5 Hz for every channel (8). The distance between the camera and the candle's plume was about 2 m.

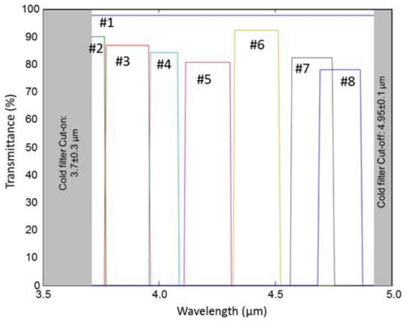

Fig. 2. Spectral transmittance of the different filters. Filter #1 (blue curve) neutral density filter/broadband, filter #2 (green curve) BP 3.7 µm, filter #3 (red curve) BP 3.9 µm, filter #4 (turquoise curve) BP 4.0 µm, filter #5 (purple curve) BP 4.19 µm with BBP, filter #6 (dark yellow curve) BP 4.45 µm, filter #7 (black curve) BP 4.63 µm and filter #8 (blue curve) BP 4.775 µm

The phenomenology associated with the combustion experiment carried out in this work by remote sensing using the Telops MS-IR MW camera is described by Eq. (2):

$$L_{tot} = \left(\left(L_{bkg}\tau_{gas} + L_{gas}\left(1-\tau_{gas}\right)\right)\tau_{atm} + \left(1-\tau_{atm}\right)L_{atm}\right)\tau_{filter}\cdots$$
$$\cdots + \left(1-\tau_{filter}\right)L_{filter} \qquad (2)$$

where L corresponds to the radiance and τ corresponds to the transmittance for the background (*bkg*), the atmosphere (*atm*), the gas from the plume (*gas*) and the filters of the filter wheel (*filter*). Since the filters are not cooled, their contributions have to be taken into account. The temperature of the filters given by the camera sensor was 23°C while the transmittance curves for all spectral filters were known (Fig. 2). The distance between the camera and the specimen was about 2 meters which is the chosen value for the atmospheric path length. For the gas plume, only water and carbon dioxide produced by a complete combustion have been considered. The amount of water produced by the plume has been fixed according to the stoichiometry in Eq. (1).

The spectral features of carbon dioxide in the MWIR are associated with the C=O asymmetric stretch. In the case of gases, broadening of the IR absorption spectrum happens as temperature increases since higher energy rotational levels are populated. This effect is illustrated in Fig. 3a for carbon dioxide at 298 K and 1000 K. An example of the atmospheric transmittance is also shown in Fig. 3b. Since the atmosphere is not fully IR translucent in this spectral range (about 4.2 to 4.5 µm) the resulting spectral radiance obtainable from Eq. (2) leads to the blue (4.18 µm) and red (4.37 µm) spike. Those two are overlaid with the spectral filter of the MS-IR camera in Fig. 3c in order to facilitate the interpretation of the signal in each filter. In addition to the red and the blue spike from CO_2, spectral features are observed in filter #7 and #8, associated with the water vapor absorption.

3. Analysis of multispectral imaging

The results of steady state candle burning through the different spectral filters of the multispectral camera are presented on Fig. 4. Each image was normalized to the IBR of a blackbody source at 85 °C in order to compare the different filters with one another. Filter #1 is a neutral density filter which is representative of a typical broadband camera. The broadband signal contrast is however less important compared to filter #5 and #6. This is due to the fact that the contribution of CO_2 relative to the whole spectral range covered by the detector is very slight.

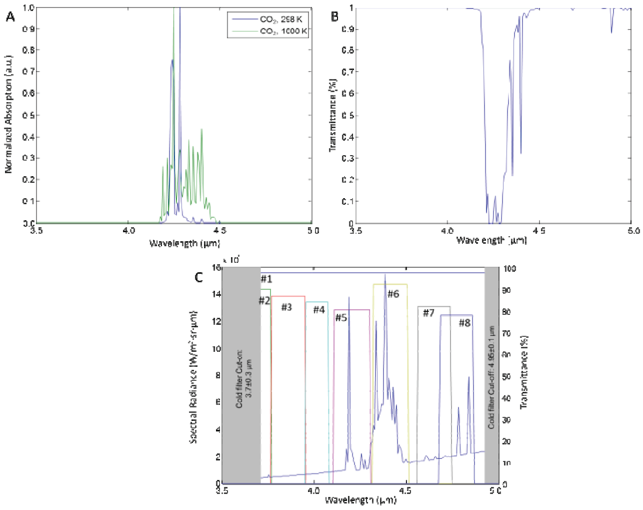

Fig. 3. Normalized IR absorption spectrum of the CO_2 at both room temperature and 1000 K (a), simulation of the atmospheric transmittance (b), resulting blue (4.18 µm) and red (4.37 µm) spike from the CO_2 (filters #5 and #6) obtained by simulation (HITRAN) overlaid on the transmittance of the 8 spectral filters for better evaluation (c)

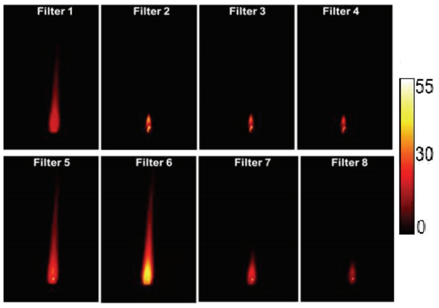

Fig. 4. Normalized IBR responses of the candle's combustion

As expected, the highest/most pronounced thermal contrasts for CO_2 are obtained through filters #5 and #6 since the CO_2 contribution relative to these filters are relatively high (as opposed to filter #1). The thermal contrast observed in filters #7 and #8, due to the water spectral features, is weaker than the one in filters #5 and #6 and this is mainly due to the fact that the contribution of the water is minor compared to the filter size in terms of width and transmittance. Very small contrasts associated with the combustion gases can be seen through spectral filters #2-4. This is somewhat expected as this spectral range (3.7–4.0 µm) is often used as "through flame" filters since CO_2 and H_2O do not emit in this spectral range [5]. One of the main advantages of using such spectral filters consists in getting information about the background radiance. Such information is valuable to estimate temperature profiles as shown in Eq. (2).

In order to prove the temporal resolution provided by the MS-IR cameras, the combustion of black powder was carried out to create a rapid combustion event. Fig. 5 shows the normalized IBR images of the burst for five wheel turns each spaced by two wheel turns.

The total sequence of explosion lasts 13 wheel turns i.e. about one second. The motorized fast filter wheel still allows an excellent frame rate: only 10 ms elapses between two consecutive frames, which gives an excellent temporal resolution for events happening very quickly.

As expected, it is possible to clearly observe the CO_2 through filters #5 and #6 and the water through filters #7 and #8 due to the greater thermal contrast provided by the absorption/emission of CO_2 and H_2O molecules respectively. The broadband signal is, as expected, not as high as the signal in filters #5 and #6. The combustion of the black powder generates a greater gases cloud, composed of CO_2 and H_2O, compared to the candle burning alone.

Using the "through flame" filters, it is even possible to detect the presence of some particles upon addition of the black powder. These particles did not show any particular spectral features thus behaving as grey bodies. These particles were attributed as soot particles which are known to behave like blackbodies.

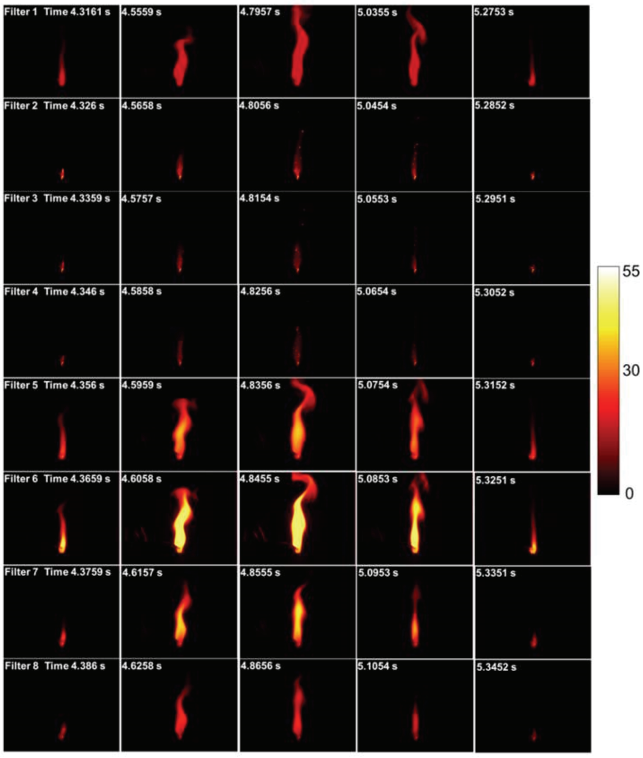

Fig. 5. Time-resolved multispectral imaging of explosion generated by black powder burning in a candle

Fig. 6a illustrates the temperature profile of the candle's plume from the broadband image (filter #1). The measured temperature of the bottom of the flame is 594.7 K while on the top of the flame it is about 440 K. By looking at the temperature provided by the use of the different spectral filters, the hottest temperature is about 900 K in filter #6 which is tuned on the CO_2 (data not shown).

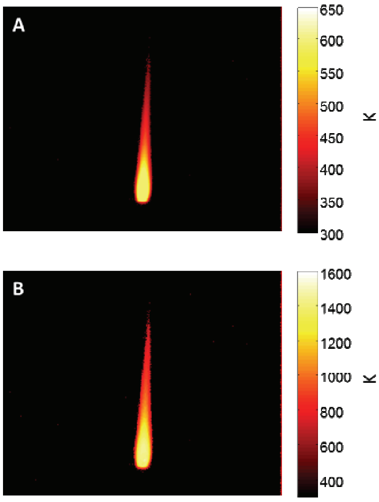

Fig. 6. Temperature profile of the candle's plume obtained by broadband imaging (filter #1) (a) and temperature profile of the flame obtained by the optimization (b)

Accordingly to the literature, the innermost zone of the flame, where the hydrocarbons vaporize and start to break down reaches about 1000°C. Formation of carbon particles continue in the luminous zone that appears yellowish due to the incandescence caused by soot ignition. In this zone, temperature is about 1200°C. The hottest temperature (1400°C) is reached in the outer zone (main reaction zone) characterized by a greater combustion due to the oxygen-rich air all around this part of the flame compared to the dark zone [6, 7]. By and large, flame temperature may be estimated to be at least about 1300-1400 K which is more than twice the value obtained using broadband imaging. Even by using data that is not saturated, infrared cameras do not allow a reliable reading of the real temperature since the emissivity of carbon dioxide is not taken into account.

Moreover, it is important to consider the radiance emitted by the background as well as the one emitted by the atmosphere in order to get reliable measurements. Thanks to the multichannel camera used for the experiment, IBR profiles are obtained. In-band radiance (IBR) consists in integrating the spectral radiance over a defined spectral range (spectral filters). By combining the information from all spectral channels, IBR profiles are obtained for each pixel. Optimization of Eq. (2) was carried out on the IBR profile of each pixel in order to estimate the gas plume temperature. The simulated IBR profiles were carried out using the HITRAN spectroscopic database. Fig.7 illustrates a typical IBR profile associated with the combustion gases obtained from the measurement. By fitting Eq. (2) using a fixed CO_2 concentration (600 ppm.m [8]) and a temperature seed set at 1500 K [9], we obtain temperature values closer to what is expected from the published literature (Fig. 6b). Moreover, the contrast associated with combustion gases is greater, which allows to have a better idea about the spatial distribution of the CO_2 and H_2O during the combustion. Due to the convection current, warm air moves up and cooler air and oxygen at the base of the candle burning flame tends to replace it, which gives the elongated shape of the flame [6]. We can thus observe through the measurement that the temperature tends to decrease as it goes up. The decrease of the temperature is also observed around the flame.

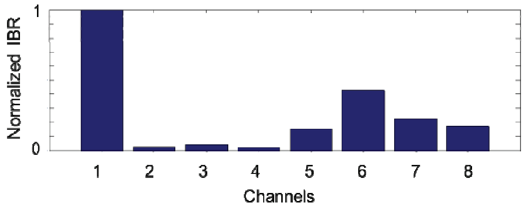

Fig. 7. Normalized IBR profile for a pixel located in the flame during the burst

The corrected temperature profile is then obtained for all the images in the sequence. Fig. 8 shows this temperature profile during the explosion generated by the black powder. Regarding the temperature profile, we can see that the warmest temperature of the flame takes more room, both in width and height. However, only 30°C difference is observed between the steady state burning and the explosion.

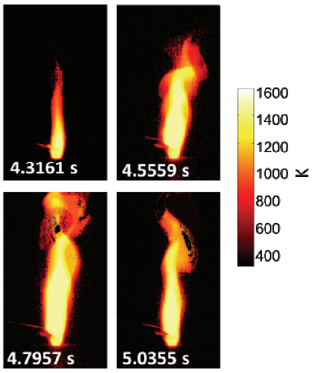

Fig. 8. Calculated temperature profile of the plume during the explosion generated by the burning of black powder

4. Conclusion

The aim of this paper was to demonstrate the importance of using multispectral measurements in order to obtain accurate temperature values by recording a burst produced by black powder in candle flame. Values obtained by optimization are twice the one obtained by broadband imaging and are similar to what it has been measured by different methods in the literature. Thanks to the multispectral camera, we obtained spatial and temporal information on candle plume temperature along the explosion. Multispectral imaging is thus a powerful tool to get information on temperature, which can be very useful for various combustion applications. Moreover, it is a wise way to get information about component produced during combustion since various components are active in a different spectral range. Cameras from the MS-IR series are affordable and allow a fast frame rate for quick event, such as combustion, these kinds of devices being the best compromise between the broadband and the hyperspectral imaging.

5. References

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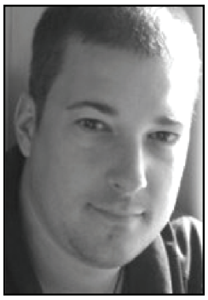

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