



On the spectral bands measurements for combustion monitoring

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ABSTRACT

In this work, spatial–spectral experimental issues affecting the detection of radical emissions in a natural gas flame are discussed and studied by a radiometric analysis of the flame spectral emission. As results of this analysis, Local and Global Spectral Radiation Measurements (LSRM and GSRM respectively) techniques are proposed, and guidelines for selecting the radical emission bands and spatial location of photodetectors are given. Two types of experiments have been performed in order to demonstrate the reliability of the GSRM technique for combustion characterization. In the first experiment, the LSRM and the GSRM have been implemented by using a home made sensor array, based on silicon photodiodes, for sensing the excited CH^{*} and C₂^{*} radicals in a natural gas flame. It has been experimentally demonstrated that by using the GSRM, the signal's dispersion can be reduced to about 86% for the CH^{*} and 76% for the C₂^{*} with respect to the obtained values with LSRM methodology. In the second experiment, the GSRM technique has been applied for sensing the CH^{*} and C₂^{*} radicals, where it has been found that the signals emissions ratio C₂^{*}/CH^{*} provides a good indicator of the thermal combustion efficiency and the CO pollutants emissions, with small dispersion. Thus, the GSRM technique has corroborated the usefulness of that ratio for combustion monitoring.

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1. Introduction

Determination of information provided by the combustion processes is nowadays an important field of development, motivated by the need to improve the thermal efficiency and to reduce pollutants emissions. This task has been tackled by the design of many sensors and techniques to carry out direct or indirect measurements for monitoring and/or controlling the thermal performance and pollutant emissions [1].

Spectroscopy techniques are particularly suitable because optical sensing of flame spectral emission uses non-intrusive methods, providing information about flame instability, O₂ concentration, CO pollutants emission, flame geometry, energy distribution, identification of elements contained in flames (molecules, atoms, radicals and ions), and also concentration variation of these elements with temperature and pressure. These optical based methods have been developed by using photodiodes [2], CCD cameras [3–5], radiometers [6–8], laser diodes [6,9], photomultipliers [10,11] and UV cells [12].

It is known that the flame spectrum conveys important information about the combustion state. However, due that the combustion

process is highly non-linear and turbulent, the information extracted from the flame's spectral emission is highly fluctuating. As result of that, wireless spectral emissions that transmit combustion information are spatially distributed along the axial and radial profiles of the flame, and they change not only with the flame turbulence (burner aerodynamics), but also with the working conditions, due to the change of the flame geometry. This means that the local spectral detection of flame emissions by means of an optical device is not representative of the global flame behavior.

An overview of modern diagnostic techniques for combustion monitoring is given by Docquier and Candel [1] where it is mentioned that the sensors may be placed at various locations, as shown in Fig. 1. Note that the spatial location of an optical sensor requires at least one optical access for sensing the spectral emission in a given spatial point in the flame. These measurement techniques are widely known and have been used to characterize the combustion process. Nevertheless, as it has been mentioned above, the sensing of these spectral characteristics in a specific point in the flame is only a sample that can not be fully representative of the actual operating conditions. Therefore, if the combustion process has been characterized by sensing some spectral information from a specific point in the flame, a problem of non-reproducibility of the result can be obtained.

Thus, in order to characterize the combustion process by means of information extracted from the flame's spectral emission, a proper measurement methodology must be defined.

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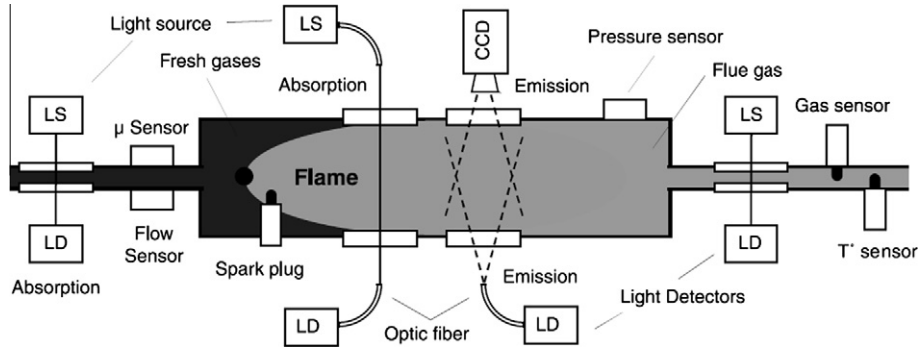


Fig. 1. Typical combustion process, sensors and diagnostic techniques for combustion control (LD-light detector, LS-light source). (Adapted from DOCQUIER and CANDEL, 2001).

The goal of this work is to provide guidelines for an effective spectral detection method. The main spatial and spectral practical factors affecting the detection of radicals emissions in a natural gas flame are identified and studied, and practical examples based on photodetectors are given. As results of that, both Local and Global Spectral Radiation Measurements (LSRM and GSRM respectively) techniques are proposed, and guidelines for selecting the radical emission bands and spatial location of photodetectors are given.

This paper is organized as follows. Spectrum emission models including spatial parameters are provided in Section 2. The spatial and spectral parameters involved in the detection of spectral bands are described in Section 3. The proposed spectral measurement technique is described in Section 4. In Section 5, the sensor's functions for LSRM and GSRM techniques are described. The developed models are experimentally validated in Section 6. Finally, in the last section, some conclusions are drawn.

2. Flame spectrum

The energy emitted by a flame is spectrally distributed in the ultraviolet (UV), visible (VIS) and infrared (IR) regions, and it has been classified in *Continuous* and *Discontinuous spectra* [13]. The continuous spectra are generally observed in the sooty region of hydrocarbon flames, where the energy is distributed in a wide band of wavelengths. Usually a maximum intensity is achieved within such band. The discontinuous spectra are attributed to the emitted energy by isolated atoms or molecules, where the energy is mainly confined around certain narrow band region of wavelengths, arranged in groups called free radicals bands. The formation of continuous and discontinuous spectra of hydrocarbon flames are summarized in the following subsections.

2.1. Continuous radiation

Hydrocarbon flames burned by diffusion show yellow luminosity due to the formation of soot. Also, in premixed flames of hydrocarbons, a CO continuum has been identified in the range of 300–550 nm [14]. It is well known that soot emits as a continuous spectrum, similar to that of a gray body but with a more complex variation of emissivity ε_λ with respect to the wavelength [13,14].

By using Wien's Law, the continuous flame radiation can be expressed as follows:

$$I_{fcont}(\lambda, T, \ell) = \frac{1 - \exp(-k \cdot \lambda^{-\alpha} \cdot (\ell_2 - \ell_1))}{k} \cdot \frac{c_1}{\lambda^{5-\alpha}} \cdot \exp\left\{-\frac{c_2}{\lambda \cdot T}\right\} \quad (1)$$

where λ is the wavelength, $c_1 = 1.176 \times 10^{-16} \text{ Wm}^2$ and $c_2 = 1.438 \times 10^{-2} \text{ mK}$ are the Planck's constants, T is the flame temperature in degrees kelvin, $\ell = \ell_2 - \ell_1$ is the observation path inside

of flame, and k is the soot concentration. According with the approach of Ngendakumana et al [14], the light absorption coefficient K_{soot} given by the soot presence, varies as a constant power of the wavelength $K_{soot} = k \cdot \lambda^{-\alpha}$, where α is a constant to be determined. Recall that the condition $\alpha = 0$ is equivalent to consider the flame as a gray body. The parameter α was found to lie between 0.7 and 1.1, while the soot concentration k was about 1×10^{-9} [14]. Eq. (1) represents the flame continuous spectral emission at one point in the flame, along the line of sight between ℓ_2 and ℓ_1 , due to the presence of soot. Note that if the observation path $\ell_2 - \ell_1$ turns to be equal to zero, there are not soot spectral emission.

2.2. Discontinuous radiation

The visible and ultraviolet optical signature in a gas flame spectrum typically consists in a discontinuous spectra from electronically excited species, denoted as chemiluminescence. Thus, energy is emitted when a transition occurs from one highest energy level j , to another lowest energy level i , of an atom or molecule. The wavelength of the emitted radiation is characteristic of the particular molecule and the particular transition that the molecule is undergoing. Quantitative analysis of the spectra is based on the existence of a definite relationship between the concentration of atoms or molecules, and the intensity of specific radicals. Thus, the emitted energy resultant in any transition is a quantum light emission of energy $E_{ij} = \frac{h \cdot c}{\lambda_{line}}$, emitted isotropically in all directions, where h is the Planck's constant, c is the light speed and λ_{line} is the emission wavelength of the line. Therefore, the intensity of an emitted spectral line I_{line} can be calculated as [13]:

$$I_{line}(\lambda_{line}) = A_{ij} \cdot N_j \cdot E_{ij} = A_{ij} \cdot N_j \cdot \frac{h \cdot c}{\lambda_{line}} \quad (2)$$

where N_j is the density population in the energy level j , and the proportionality coefficient A_{ij} is the Einstein transition probability of spontaneous emission.

Like the continuous emission, the intensity emitted by a spectral line is the integral of the intensities emitted along the observation path $d\ell$ at temperature T . Therefore, the intensity of an emitted spectra line is given by:

$$I_{line} = \frac{\delta}{\lambda_{line}^3} \cdot \exp\left(-\frac{E_j}{KT}\right) \cdot [1 - \exp(-\beta \cdot (\ell_2 - \ell_1))] \quad (3)$$

where

$$\delta = 8 \cdot \pi \cdot h \cdot c \cdot \frac{f_{ij}}{f_{0j}}$$

$$\beta = \frac{\pi \cdot e^2}{m \cdot c} \cdot \frac{g_i}{g_o} \cdot f_{0j} \cdot N_0$$

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