A measuring method based on photodiodes for the diagnostic of optimal combustion conditions

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Abstract

A non-intrusive method for monitoring flames in gas burners is presented. The method is based on the optical analysis of the flame by using a Silicon Photodiodes array and a set of interference optical filters. The covered wavelengths evaluate the formation and behaviour of excited CH* and C_2* radicals for confined gas flames. The monitoring of these radicals is carried out in the flame reaction region at the burner exit, where the C_2*/CH* ratio signals provide enough information to identify the optimal fuel–air ratio in order to obtain the boiler maximal efficiency and to prevent an incomplete combustion. The experimental results obtained for two power levels, in a boiler of 150 kW, demonstrate that the C_2*/CH* ratio provides important information concerning the combustion state and gives a clear indication about the burner adjustment when CO emissions begin to increase to the upper the levels accepted by environmental laws. The fast response and its non-intrusive character give to the proposed optical sensor an important potential to be used in advanced control strategies for the on-line optimization of the combustion process.
Keywords: combustion, gas, flame spectrum, photodiodes, optimization, optical sensor.

1 Introduction

The monitoring of the combustion state in boilers and industrial furnaces is limited due to the hostile environment. Indeed, the high temperature, the corrosive atmosphere and the limited access to the flame characteristics restrict a reliable diagnostic. The information provided by conventional combustion

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instruments is clearly insufficient to act on the burner settings, which would be an effective way to optimize the flame, to operate at high thermal efficiency, reducing emissions of carbon monoxide and/or nitrogen oxides. Thus, the development of wireless sensors with a non-intrusive character is highly important.

The application of control techniques for combustions systems is of great interest. However, reliable combustion control techniques need reliable sensors and this depends on the characteristics of the combustion process. In this case, many groups of sensors has been analysed and applied at an industrial level [1,5]. For gas sensing, the following classes of sensors have been revised:

- Solid electrolyte ZrO_2 sensors for O_2 and CO.
- Solid electrolyte, non-nernstian ZrO_2 sensor for CO/H_2.
- Thin-film semi-conductor sensors (SnO_2, Ga_2O_3, Nb_2O_5) for oxidising or reducing gases.
- Thermal conductivity sensor for CO_2.
- Sensors and optical methods using radiative properties of flames: spectrometry, spatio-temporal signature.
- The potential of some generic technologies being developed, in particular those using laser diodes and those using diamond coatings.
- Optical methods using the flame signature principle.

The optical methods, used in the characterization of combustion quality and pollutant emissions by means of the flame signature principle, have been studied and developed in many works. However, their application at an industrial level is difficult today [1,5].

In particular, the massive use of radiometric techniques [3,4,7,10,11,22] has contributed to a better understanding of the combustion processes. It is known that in the reaction zone of hydrocarbon flames, the oxygen of the air reacts with the fuel to liberate the chemical energy stored in the molecular bond. This energy is reflected in the visible flame spectrum around certain narrow wavelengths and a continuous background. The discontinuous spectra of atoms or molecules are arranged in groups, each group being called a band of free radicals [2]. A typical case of gas flames burned by diffusion into the surrounding air show yellow luminosity due to the formation of soot. Soot emissions are similar to that of a grey body but with a more complex variation of emissivity with the wavelength [3,12]. In gas premixed flames, a CO continuum has been identified in the range of wavelength from 300–550 nm [3].

The radical's intensities detection has been greatly used to obtain the combustion state index. The radicals better detected are those found in the short wavelength, because of having a lower interference with the emission of soot particles. In this case, CH* (at 432nm) and C_2* (at 516nm) radicals are very interesting because they provide easily observable signals, with a strong intensity, and their radiation is spectrally resolved. OH* radical (306-315nm) is attractive because of the reduced background emission at this wavelength. On the other hand, the CH* radical has been identified as the best marked on the flame front and it is often used as a measure of the heat release rate. In many works, the intensity emissions and the ratio of different radicals have been used in order to identify clearly the main flame zones, air–fuel ratio, and pollutant emissions amongst others. Thus, the ratios CH*/OH*, C_2*/OH* and C_2*/CH* show a nearly linear function of equivalence ratio [19,22]. Also, the correlation between chemiluniscence of any radicals and the flame temperature has been investigated [22].

The study and application of sensitive photodiodes in the UV-VI range, for spectral emission detection, was carried out in the last 10 years. However, the polarisation mode of these photodetectors is not mentioned. Khesin [14,15] applied photodetectors to realize combustion control in pulverized coal burners at an industrial level, by measurement of the flame instability. In recent years a method based on a Si photodiode (with spectral response 190-1100nm) has been used [17,18]. The signal of this sensor integrates the contribution of different excited radicals and continuous spectra and uses the rms average of the 'flame luminosity', which is compared with the CO emissions. Also, a Photomultiplier has been used with an optical filter in 310 ± 10nm to detect the OH* radical intensity. Another method is based on the utilization of UV cells [16], which is based on Si (UV enhanced) and GaP junctions and the signal generated by the photodetectors is acquired and post-processed. The light is collected by means of a lens and optical fibre and the detector cell is installed in a tube, inside the burner. A correlation has been obtained between O_2 emissions and the flame stability, but this correlation changes for different boiler geometry, burner/boiler types and load.

Additionally, others techniques have been used by means of the flame spectrum. For example, the flame temperature has been estimated by using the two or more wavelengths methods, through the spectral emission measurement of soot particles [2,3,9,11]. Moreover, the gas emission has been estimated through absorption spectroscopy by using laser diodes [1,5,6]. On the other hand, different camera technologies have been used to define combustion parameters from the flame morphology [19,21].

The flame spectrum intensity depends on many variables such as the temperature, the kind of gas mixture, fuel–air ratio, the burner type, the turbulence, and the flame area observed. Therefore, the main purpose of this investigation is to characterize the influence of the combustion parameters by use of a photodiode array in order to propose an optimal combustion control system. Thus, an optical method for monitoring flames in gas burners is developed. Further, the optical analysis of the flame is achieved by using a Silicon Photodiodes array and a set of interference optical filters. The optical sensor is able to measure the C_2* and CH* signals, and the ratio of these radicals provides enough information to identify the optimal fuel–air ratio in order to obtain the boiler maximal efficiency and to prevent an incomplete combustion.

2 Monitoring a gas flame by using photodiodes

The objective of this paper is to describe the advantage of the photodiodes utilization in order to determinate the combustion state and use this information for a combustion control strategy.

In this paper, a new monitoring method for CH* and C_2* radicals, by using silicon photodiodes equipped with optical filters centered in the corresponding emissions bands is presented.

The spectral responsivity of these devices is between 380–1200nm, with a maximal response at 850nm. The center wavelength of filters for detection of CH* emissions is 430 ± 5 nm and 514.5 ± 5 nm for C_2* emissions, with a transmission of 45% and 70%, respectively. The difference between the filter transmission and responsivity intensity was corrected by software. The polarization mode for driving the photodiodes signals was the Photoconductive. Thus, a linear response is obtained by using this mode between the photon incidence and the current generated.

The flame area covered by the photodiodes is observed from the exit burner. The specific installation of these devices is shown in figure 1, where the photodiode array is cooled by means of fresh gas and air flux and the distance between the photodiodes and the flame basis is 8cm. The reaction zone is observed, with a FOV of 72º, where the formation of these radicals is strong [3,22]. The experimental results were performed in a central heating boiler of 150 kW, equipped with a Riello GS20 gas burner. The test bench was instrumented with gas and water flow meters, thermocouples and gas analyser (at the exit of the chimney) in order to obtain the on-line parameters of combustion and boiler efficiency. The photodiodes driver's signals were recorded in the computer by using a DAQ board at 100 kHz, and processed by the LabView interface. The tests reported in this paper were performed covering two firing rate values: 150 and 130 kW.

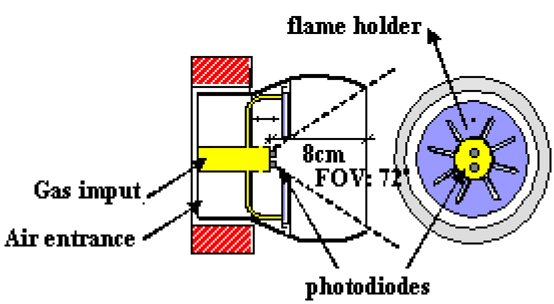

Figure 1: Photodiodes installation.

3 Experimental results

Figure 2 show the spectral intensity of the gas flame, obtained from the burner exit by using the USB2000 Radiometers operating in the visible range. It is possible to distinguish clearly the main bands of CH* and C_2* radicals. One verifies that the main reacting zone may be characterised by these specific emissions and provides more observable signals to be monitored by the photodiode array.

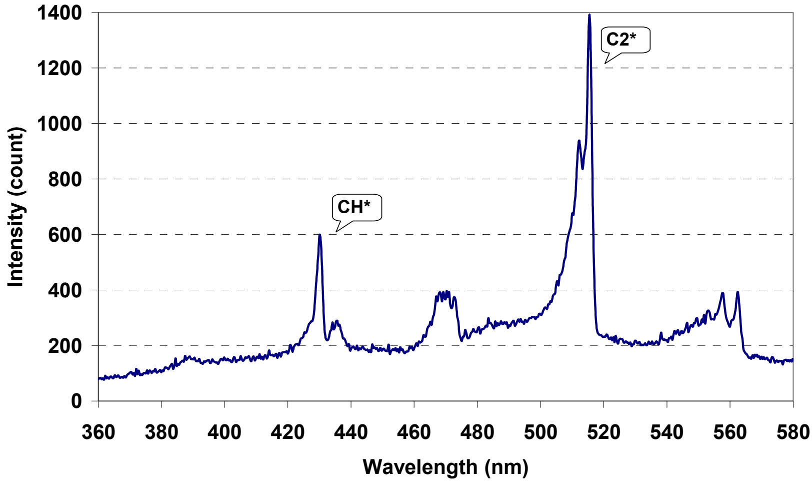

Figure 2: C_2* and CH* radicals at the reaction zone.

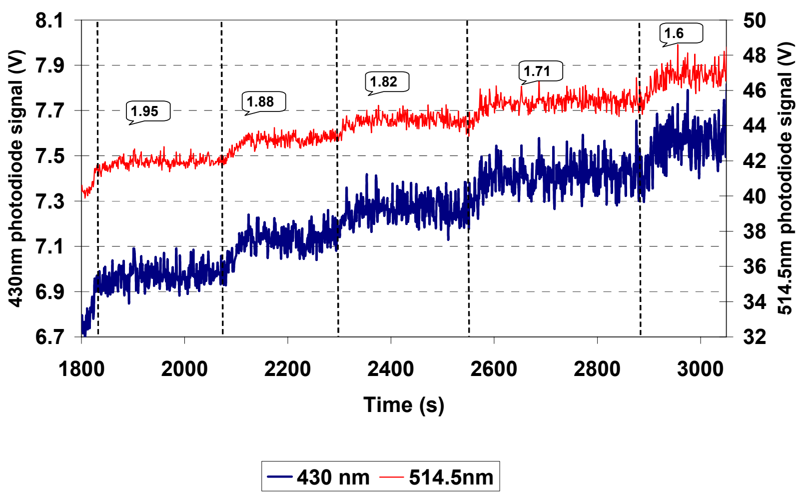

Figure 3: On-line response, photodiodes at 430 and 514.5nm.

In the tests performed, the air flow was decreased by closing the burner air damper and the real time response of the photodiodes and gas analyzers were registered. Figure 3 shows the online response of the photodiodes, for different air excesses (Lambda=1+e), where it's possible to observe that the change in the air flow is followed by the array sensor. Also, as in figure 2, the C_2* radical intensity is stronger than the CH* radical. The great difference between the

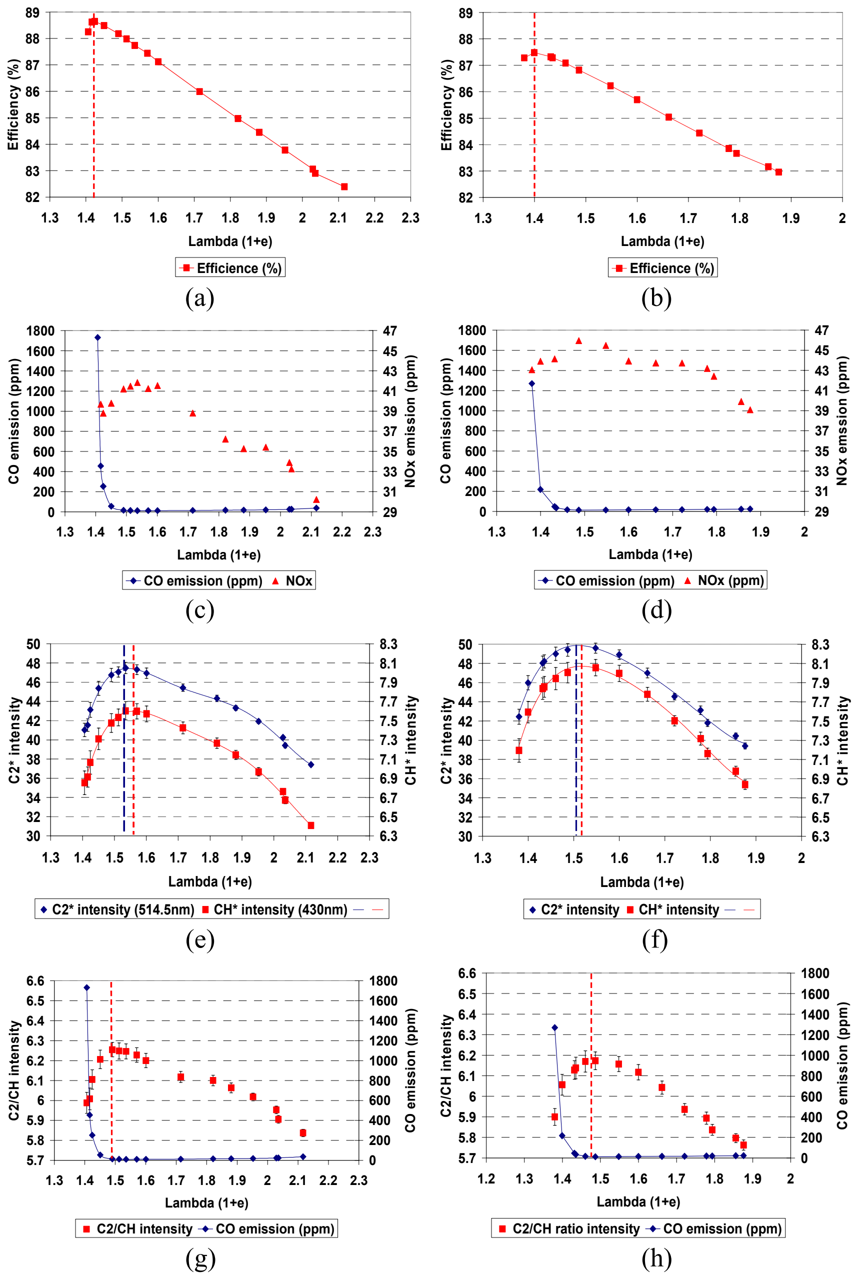

Figure 4: Test boiler resume for two power levels: 130 kW (in left column) and 150 kW (in right column) for change in the air excess. (a,b) Thermal efficiency (c,d) CO and NOx emissions. (e,f) Absolute intensity of CH* and C_2* radicals detected by the photodiodes array. (g,h) C_2*/CH* intensity ratio.

intensity of these signals is because the filters have a FWHM (full width at half maximum) of 10 nm. In this case, the integrated signal from the photodiode at 514.5 nm is bigger than photodiode at 430 nm

Figure 4 shows the results of the boiler performance and the radical emissions for two levels of boiler power (130 and 150 kW), as a function of the excess air. The optimal operation condition is clearly given by critical excess air when CO emissions increase abruptly and the boiler efficiency began to decrease at low levels of air excess, as show in figure 4 (a, b, c and d).

From the point of view of the pollutant emissions, the trends of NOx curves (figure 4, c and d) are very similar to the radical emissions (e and f). The intensity emissions of both radicals, CH* and C_2*, show a similar behaviour. The maximal levels are achieved at excess air values higher than the critical one defined by increased CO. However, these maximal levels shows a slight diphase for CH* and C_2* radicals, according to the observations of Gaydon and others [8,3].

In figure 4 (g and h) one can observe the trends of the C_2*/CH* intensity ratio, which increases while excess air decreases to a level near to the critical point of incomplete combustion, i.e. when CO increases abruptly.

4 Conclusions

The experimental result shows that the C_2*/CH* intensity ratio is a good indicator of the combustion state, because it permits prediction of the point of optimal air excess condition in order to obtain the maximal efficiency of the equipment, assuring a low level of pollutants (CO and NOx). This fact has been verified for two power conditions of a gas boiler. From this result it is possible to perform an optimal strategy of combustion control.

The fast response, non-intrusive character, and low cost yield to the developed optical sensor is an important potential to be used in advanced control strategies for the on-line optimization of the combustion process.

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