Journal of Mechanical Engineering and Sciences (JMES)
ISSN (Print): 2289-4659; e-ISSN: 2231-8380; Volume 9, pp. 1604-1613, December 2015

DOI: http://dx.doi.org/10.15282/jmes.9.2015.8.0156

# Analysis of industrial flame characteristics and constancy study using image processing technique

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## ABSTRACT

The study of characterizing and featuring different kinds of flames has become more important than ever in order to increase combustion efficiency and decrease particulate emissions, especially since the study of industrial flames requires more attention. In the present work, different kinds of combustion flames have been characterized by means of digital image processing (DIP) in a 500 kW PF pilot swirl burner. A natural gas flame and a set of pulverized fuel flames of coal and biomass have been comparatively analyzed under co-firing conditions. Through DIP, statistical and spectral features of the flame have been extracted and graphically represented as two-dimensional distributions covering the root flame area. Their study and comparison leads to different conclusions about the flame behavior and the effect of co-firing coal and biomass in pulverized fuel flames. Higher oscillation levels in co-firing flames versus coal flames and variations in radiation regimen were noticed when different biomasses are blended with coal and brought under attention.

***Keywords:*** Flame characteristic; flame stability; image processing; swirl burner.

## INTRODUCTION

Flame visualization-based systems are preferred for online monitoring of combustion processes because they are non-intrusive and cost-effective techniques which allow detection and control of operating problems. Physical flame characteristics, i.e. its geometric and luminous parameters, temperature distribution or its oscillation frequency, provide detailed information about combustion efficiency and stability, which can be used to develop optimization strategies of monitoring and control algorithms [1-6]. Different research groups have investigated pulverized fuel flames by using advanced digital processing of flame images acquired with CCD (charge-coupled device) cameras, enabling the extraction of relevant flame features [7-13]. Some of these studies aimed to establish possible relationships between image features as well as operational and performance parameters such as swirl number or NOx emissions in both gas and pulverized fuel flames [14-17]. Research on this topic could be an important support for the introduction of biomass fuels in conventional power plants, especially in Southern Europe where it is very scarce to date. Co-firing is a very promising strategy to reduce $CO_2$ emissions and lessen the current dependence on non-renewable energy resources, which is particularly relevant given the current political situation in the Middle East and Northern Africa. In spite of the obvious advantages of biomass, it poses some important challenges to be overcome. The influence of some operational parameters, such as different air ratios, fuel composition or particle size distribution on flame structure and emissions, must be investigated and quantified in order to avoid losses in efficiency or unexpected problems [18, 19]. The aim of this study is to investigate the industrial flame characteristics and constancy study using image processing technique.

## EXPERIMENTAL SETUP

### Methods and Materials

In this experiment, a flame diagnostic system, based on a high-speed CCD camera, has been implemented in a 500 kWth PF pilot swirl burner. Dedicated algorithms have been developed to extract meaningful features of the flame from the registered images. As luminous parameters and the weighted averaged frequency is brought under focus, the so-called flicker frequency is observed [4]. The objective of the present study is to analyze the flame behavior and its main features, under different conditions and fuels, using advanced processing of digital images. To this end, a test program covering different conditions has been conducted in the experimental combustion facility. Preliminary results about the characterization of different kinds of flames, focusing on biomass-coal and co-firing flames, are presented here.

### Combustion Facility and System Installation

For the present application, flame monitoring system is constituted by a CCD (charged-couple device) high speed camera (JAI CM-030 PMCL-RH), which is the main part of the system (Figure 1). It is equipped with an optical system which expands the field of view. The camera achieves a frame rate of 120 frames/second with a resolution of 659 (h) x 494 (v), but it is capable of reaching a rate of 504 fps with partial scan mode. Electronic shutter, used to limit the registered radiation and avoid saturation, was permanently fixed in order to compare different videos and it is equal to 1/10000 seconds [20]. The optical and electronic parts are integrated as a single unit and inserted into a protective system that consists of a stainless-steel cylindrical probe equipped with a water cooling circuit which maintains the system under a secure temperature (15ºC). Purging air permanently keeps the objective free from dust and limits fouling. The combustion test facility, where the monitoring system is implemented, is a downshoot multifuel vertical swirl burner with a nominal power of 500 kW. The pilot plant is able to operate with pulverized fuels such as coal, biomass or blends. It is equipped with a natural gas-fuelled ignitor of 35 kW used for preheating and security reasons, which is used in the present study as an example of a gas flame. A detailed description of the test rig can be found in previous works [21, 22]. The visualization probe is inserted through one of the inspection ports placed at the upper part of the combustion chamber. In order to guarantee a proper flame view, the CCD camera is located at the nearest port to the burner throat (Figure 2). This view is limited by the focal length, which is 7 mm. With this arrangement, the captured flame area is approximately 315 mm x 230 mm, considering a distance of 400 mm to the flame and the pixel resolution is approximately 0.23 $mm^2$.

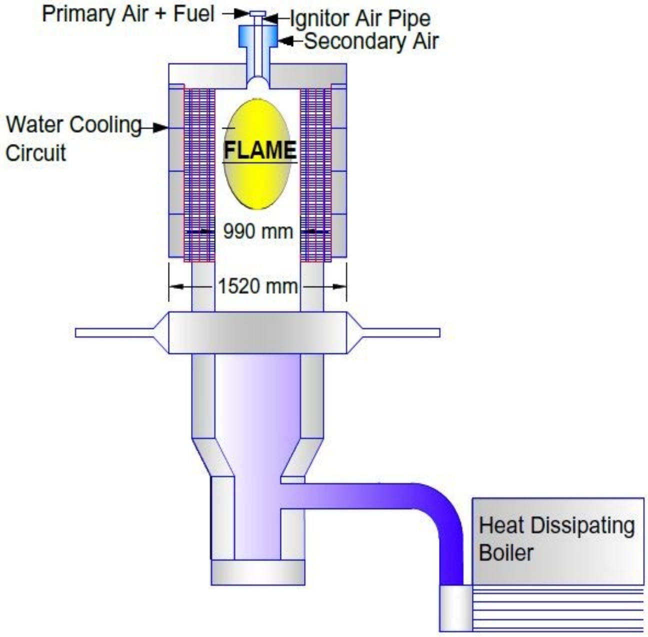



Figure 1. Flame monitoring system location in the combustion furnace.

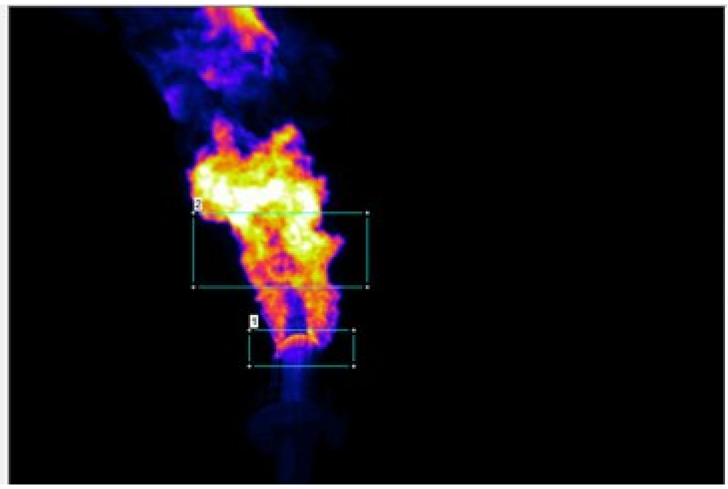


Figure 2. Industrial flame under high speed camera vision.

**Test program and fuels**

The experimental program contained some tests with a natural gas flame in order to validate the monitoring system and obtain information related to this kind of flames. The rest of the program was devised to cover several flame states and basically compare the possible variations in flame features when co-firing biomass and coal. In order to detect the differences between coal and co-firing flames, similar operational parameters were maintained during the combustion tests, i.e. similar primary air/fuel ratio (2.3 kg air/kg fuel), air excess (34%), swirl numbers (1.54 for primary air and 0.86 for secondary air) and furnace pressure conditions (-200 Pa). The program included several tests using South African coal and two different kinds of biomasses, Spanish forestry-wood residue (pine chips) and an energy crop (*Cynara cardunculus*), which is considered as a potential fuel for power generation. Proximate and ultimate analyses as well as low heating value of each fuel were determined according to European standards. Maximum biomass particle size was 0.500 mm, and 0.100 mm for coal. Biomass particles usually present a different morphological structure from coal (they are more irregular in shape than coal), which could be an important aspect to consider when studying co-firing flames [23]. Fuel characterization is presented in Table 1.

Table 1. Fuel characterization.

| | Cynara | Pine | Coal |
|---|---|---|---|
| Moisture (%) | 10,90 | 8,57 | 2,30 |
| Proximate | Analysis | (% d.b) | |
| Ash Content | 6,61 | 1,65 | 14,60 |
| Volatility | 73,80 | 79,89 | 26,00 |
| Fixed Carbon | 19,59 | 18,46 | 59,40 |
| Ultimate | Analysis | (% d.b) | |
| Carbon | 46,25 | 49,47 | 69,60 |
| Nitrogen | 1,05 | 0,52 | 2,05 |
| Hydrogen | 4,94 | 4,86 | 4,00 |
| Chloride | 0,95 | --- | 0,01 |
| HHV (kJ/kg)(d.b.) | 19320 | 19587 | 27800 |

## RESULTS AND DISCUSSION

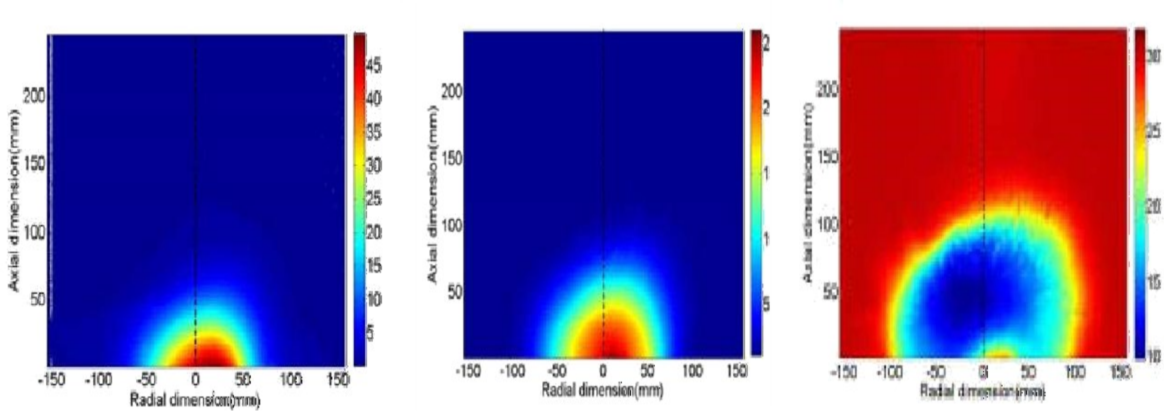
### Measurement principles

The analysis is made over videos, which are basically a sequence of flame images. The information is extracted from the radiation intensity registered by each individual cell of the CCD sensor and stored in each pixel of the image as a value ranging from 0 to 255. These values reflect thermal radiation emitted by the flame and they change with time. Finally, a three-dimensional data matrix, consisting essentially of a huge collection of temporal values, is obtained. The procedure of digital processing is summarized (further details in Ref. [20]). As a first step, each image is properly corrected in order to minimize thermal fluctuations and electronic noise from the camera, as well as the non-uniformity in the pixel responses [24]. This procedure simply consists of the subtraction of a suitable master mask (previously obtained from a video captured in absence of light) to each individual frame. Afterwards, statistical and spectral features are calculated from the temporal signal of each individual pixel, providing a two-dimensional characterization of the flame. The statistical magnitudes considered in the analysis are: the standard deviation and the averaged grey level, which can be interpreted as the amplitude of the flame luminous fluctuations and flame brightness intensity, respectively. Also, flicker is being calculated using Fast Fourier Transform (FFT) apart from those statistical parameters. Fluctuation in flame is caused by many reasons like uneven heat release, improper mixing and the result eddies present in a flame. Flicker represents the mean frequency of the flame flicker. Therefore, it can be used as reckoner for different flame types and combustion efficiency.

### Gas flame

Firstly, a natural gas flame is analyzed. It has a thermal input of 35 kW and its location is concentric to the pulverized fuel burner. Owing to the fact that the gas ignitor tip was located inside the PF swirl burner throat, the gas flame was not completely recorded by the CCD camera. However, the visible part can be easily analyzed and some interesting characteristics can be studied. Figure 3 illustrates the two-dimensional distribution of the main statistical and spectral parameters in the gas flame case, that is: averaged grey value, standard deviation and flicker frequency. The axes represent in mm real dimensions of the captured area as per the distance and focal length indicated. The horizontal axis corresponds to the radial dimension and the origin concurs with the center of the nozzle. Therefore, the vertical axis represents the longitudinal dimension of the combustion chamber. Brightness distribution indicates that the flame presents several concentric zones caused by the emission of radiant energy from the flame. Also, brighter parts are situated just in the burner outlet. Since the grey level is, in a non-rigorous sense, related to the temperature, brightness distribution shows a rough map of flame temperatures [25]. According to standard deviation values, the inner zones show higher amplitudes indicating wider fluctuations in heat release.

Regarding flame oscillation, the averaged frequency in the registered area is around 10-20 Hz, which agrees with previous publications related to measurements in gas flames. Flicker signal in such flames usually shows multiple dominant frequencies, which increase with the drop of the equivalence ratio [4]. According to the frequency pattern shown in Figure 3(c), the inner part of the flame has lower flicker frequencies, leading to higher levels outwards and near the burner outlet. High frequencies registered outside the flame area are due to the remaining background noise in the signal which, however, does not have influence when the flame is present. Considering all variables, some conclusions can be drawn. Firstly, maximum levels of brightness do not correspond to areas of wider fluctuations, indicating that they are indicators of different phenomena, specifically temperature and luminous oscillation, respectively. Furthermore, flicker distribution offers a different interpretation of the flame according to its oscillating areas. Finally, as can be observed in the three graphics, certain asymmetry in the flame shape is observed.



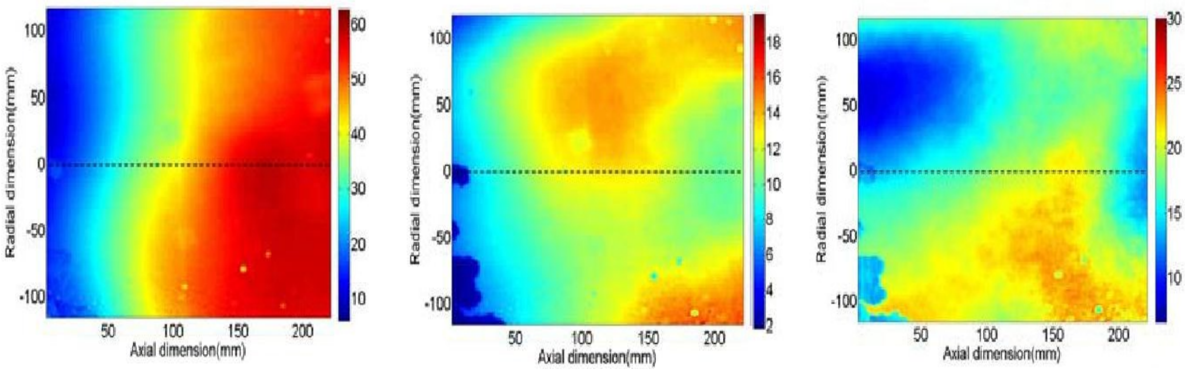

(a) Brightness (%) b) Fluctuations amplitude (%) c) Flicker frequency (Hz)

Figure 3. Two-dimensional distribution of a natural gas flame.

**Pulverized fuel flames**

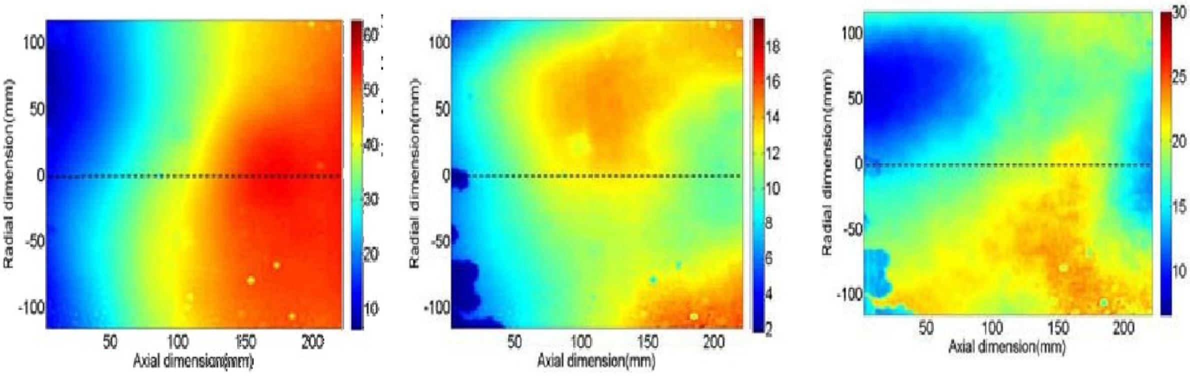
Two kinds of pulverized fuel flames were analyzed: a pure coal flame and a coal-biomass co-firing flame. Although flame contour cannot completely be registered due to flame size and practical limitations, the main part, which is the root region, is recorded. As in the previous section, averaged grey value (brightness), standard deviation (fluctuation amplitude) and flicker distribution are represented and compared for the pulverized fuel flames. In order to select a suitable flame area, the camera system was rotated with regards to the previous position, as described in Section 3.2.1. With the current orientation, horizontal axis corresponds to the longitudinal dimension of the furnace and the vertical one to the radial dimension, being the burner throat on the left side. Likewise, axes represent actual dimensions, and the same distance to the flame is considered. In spite of the purge system, some dust and moisture deposition around the objective could not be avoided, but it did not influence the interpretation of results. For comparison purposes, the selected videos were recorded at similar temperature conditions (around 945 ºC) and flue gases emission levels, which were kept as low as possible. In particular, the registered CO concentration, the main estimator of combustion quality, was below 400 mg/m$^3$N in all tests.

The following figures represent the resulting graphics for the three flames tested, pure coal flame (Figure 4), coal -*cynara* (Figure 5) and coal-pine (Figure 6) co-firing flames. In the last two cases, the substitution percentage was 10%, in an energy basis. Coal-pine co-firing tests were performed with the visualization system rotated 90 degrees with regards to other tests. Because of that, in order to allow comparisons, the graphics just show the common area recorded in the two orientations.



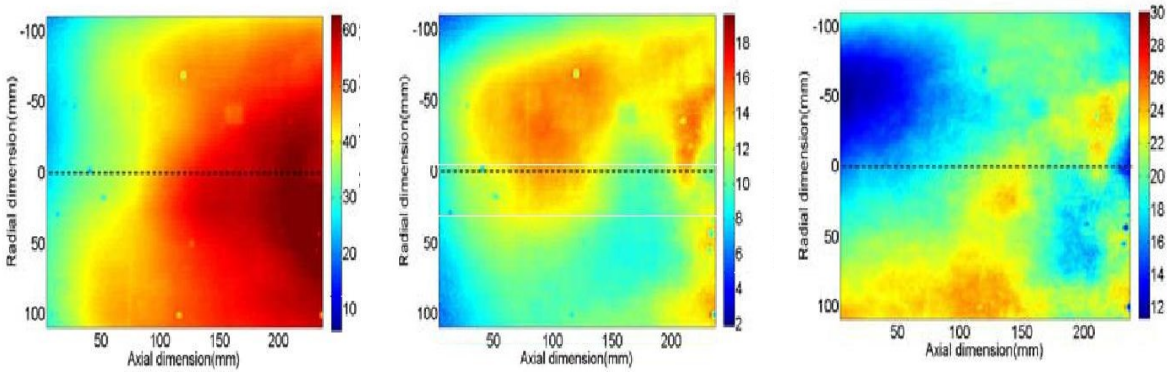

(a) Brightness (%) b) Fluctuations amplitude (%) c) Flicker frequency Hz)

Figure 4. Two-dimensional distribution of a pure coal flame.




a) Brightness (%) b) Fluctuations amplitude (%) c) Flicker frequency (Hz)

Figure 5. Two-dimensional distribution of a co-firing flame with *Cynara*, 10% substitution.




a) Brightness (%) b) Fluctuations amplitude (%) c) Flicker frequency (Hz)

Figure 6. Two-dimensional distribution of a co-firing flame with pine wood, 10% substitution.

According to the standard deviation values, fluctuations amplitude is also wider for a coal flame where most of the areas have a standard deviation values around 18 %. This means that there are variations in heat release when biomass is included as an additional fuel. Higher brightness values do not match wider fluctuation areas, indicating again that they are related to different phenomena. Concerning flicker frequency distribution (Figures 5c and 6c), larger areas with higher oscillation frequencies are found in the co-firing flames regarding coal (Figure 4c). Usually, a higher flicker frequency is associated with better combustion performance; so, in light of the results, biomass addition could favor a more stable flame being positive for the process [26]. In fact, in the current co-firing tests, NOx and SO2 emissions were slightly lower than those registered on pure coal tests [27]. One common feature in the flicker distribution of the three cases is the low frequency in the circular area near the burner throat, which is due to cold flow entrance. Also, certain asymmetry is observed in the distribution of luminous and spectral parameters, which is a known behavior in swirling flows gathered in numerical simulations [28]. Comparing the two co-firing cases in Figure 5 and Figure 6, a noticeable difference regarding mean value distributions is observed. When coal is co-fired with pine wood, a small area with higher brightness is appreciated in the right side of the graphic, 200 mm from the burner exit. The fluctuations amplitude in the flame luminosity, represented by standard deviation values, show higher levels for pine wood co-firing than for *cynara* co-firing. In the same manner, pattern modifications in the distribution indicate differences in heat release. This can be related to the higher volatile content of the pine wood compared to *cynara,* and the differences in biomass density and particle shape, which could affect the mixing dynamics and combustion stages [1]. That difference could also be the reason why the coal-pine flame seems to be closer to the burner exit. In regards to flame flicker, slight differences are observed for co-firing with respect to the pure coal test. The coal-pine flame shows similar frequency levels as those registered in the coal-*cynara* flame, but they are differently distributed, which may be due again to variations in mixing dynamics. This aspect is currently under analysis and further research, regarding particle shape, which will be made in order to establish the possible influence. Averaged grey values (brightness) in the coal-pine flame are clearly higher than in other flames. This effect can be explained by the fact that biomass has a noticeable higher volatile matter than coal and produces a brighter flame [18]. However, coal-*cynara* flame does not show such high values, which can be due to the higher humidity level and ash content.

## CONCLUSIONS

Experimental research designed to investigate the characteristics and stability of different kinds of combustion flames has been carried out in a 500 kW PF pilot swirl burner. The reliability and feasibility of a flame visualization system based on a high speed CCD camera has been demonstrated, allowing for the development of diagnostic and control algorithms in the future. Statistical and spectral parameters provided by appropriate digital signal processing give a detailed characterization of the flame and the combustion processes that take place. The usual procedure for a flame characterization found in the literature consists of obtaining flame parameters measured over the luminous region of the images and to express them as global data. On the contrary, present work gives two-dimensional distributions of flame characteristics, offering a quantitative description, which preserves more complete information about the combustion process of different types of flames used in industries. This work is dedicated for better understanding of different kinds of flames as well as their behavior when different biomasses are co-fired with coal in such burners. Apparently, small co-firing rates of biomass do not influence the behavior of the pulverized coal flame and could even be positive, according to the higher fluctuation levels achieved.

## ACKNOWLEDGEMENTS

The authors would like thanks to Department of Mechanical Engineering, Rungta College of Engineering and Technology, Bhilai, India for their assistant and help.

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