Combustion diagnosis by image processing

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Abstract— The paper presents an application of image processing for detection of combustion instability and characterization of pulverized coal combustion. Several shape parameters have been used, such as flame area, coordinates of its center of gravity, contour length as well as its Fourier descriptors for qualitative description of the flames. Experiments were done in a scaled down laboratory facility.

Low-emission combustion techniques of pulverized coal decreases the emission of nitrogen oxides but, on the other hand, spoils combustion stability and decreases combustion efficiency. Possible results are flame shifting and even flame extinguishing that could lead to a sudden ignition of unburned fuel inside a combustion chamber. Additionally, adding a secondary, renewable fuel such as biomass spoils the combustion process. It also results in a increase in corrosion and boiler slagging.

There are many diagnostic methods of a combustion process but they give delayed and averaged results, the others are expansive or unfit for industry [1]. Moreover, at the present moment the method of direct measurement of the amount of coal dust supplied to the burner - the so-called primary air- does not exist. One of the quickest ways of obtaining information about the combustion process is analyzing its radiation. In the case of pulverized coal combustion, semiconductor detectors for an infrared and visible wavelength range are generally utilized, which is inexpensive and can be easily arranged in arrays or matrixes.

Shape analysis has been a matter of constant attention in computer vision. The shape of a flame is related to spatial distribution of chemical species produced during the combustion process. Changes in combustion inputs modify the geometry of a flame [2,3]. In order to make objective assessment of combustion, some of flame image parameters have been investigated such as: flame area, flame center coordinates, length of a flame contour and its Fourier descriptors. The paper presents their application for combustion diagnos.

The test stand of a horizontal layout consists of a cylindrical combustion chamber, 0.7m in diameter and 2.5m long and it is presented in Fig.1.

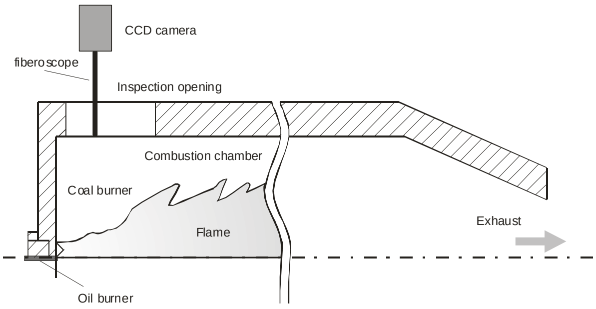

Fig.1. CCD camera mounting in an inspection hole of the combustion chamber.

A model of low-NOx swirl burner ap. 0.1 m in diameter is mounted at the front wall. The stand is equipped with all the necessary supply systems: primary and secondary air, coal, and oil. The oil heater heats primary and secondary air. Additionally, electrical heaters tune final temperatures of the air. Oil and gas systems also provide oil and gas for the guns which can be located in the very center of the coal burner. Pulverized coal for combustion is prepared in advance and dumped into the coal feeder bunker. A two-worm dust conveyor supplies coal dust to a primary air duct. The combustion chamber has two lateral inspection openings on each side, which enables image acquisition. A typical CCD monochrome camera was used. It was capable of acquiring 25 frames per second. To avoid adverse influence of high temperature on camera work, it was equipped with a 0,7m fiberoscope that transmits the flame image [4]. A general view of the combustion facility as well as that of CCD camera mounting details is shown in Fig. 1.

A typical combustion test consisted of the following steps. First, the combustion chamber was warmed up with oil. When the temperature had risen high enough, the feeding device was started and the air-coal mixture was delivered to the burner, simultaneously with oil. After reaching the proper temperature level, oil supply was switched off. Primary air is used mainly for delivering pulverized coal to the burner nozzle, while secondary air is used for regulation purposes. The input parameters of the burner, i.e. coal and air flow, were changed several times during the tests so as to bring about various combustion states.

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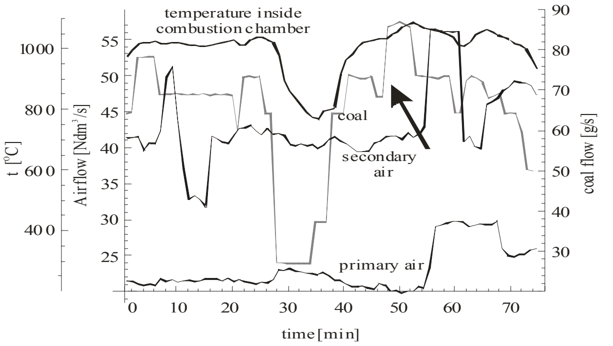


Fig. 2. Typical values of temperature inside the combustion chamber, coal and air flow during a combustion test.

Changing air-fuel ratio causes temperature changes inside the combustion chamber as shown in Fig.2. The temperature inside the combustion chamber was measured in its axis, about 1.5m in front of the burner. Unstable combustion has occurred when the coal flow suddenly increased, which was depicted in Fig.3 with an arrow.

Video data were represented as a sequence of 8-bit monochrome images. Since the distance from the fiberoscope to the flame is much smaller than the flame length, only a part of the flame placed near the burner nozzle was observed.

As combustion input parameters vary in time, they influence the shape parameters of a flame. Determining these parameters requires extracting the flame region out of a given image. The flame region was arbitrary defined as a set of pixels that have more than 80% of the maximum possible brightness. There were no luminous objects, except the flame.

The flame center coordinates are calculated as the mean value of line or column coordinates, respectively, of all pixels contained within the flame area. A state of unstable combustion could be easily pointed out by the shift of flame center coordinates, which could be seen in Fig. 3.

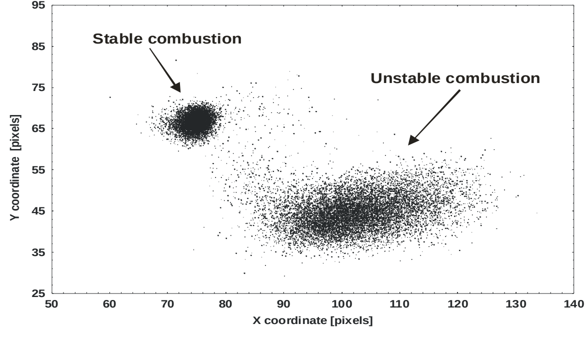


Fig. 3. Flame center coordinates for stable and unstable combustion.

It is worth noticing that stable combustion corresponds to lower variability of the flame center coordinates.

Similar analyses were applied to the flame contour. Its length was defined by counting the distance between all the adjacent boundary pixels. The distance between the two neighboring contour points parallel to the coordinate axes is rated 1, whereas the distance in the diagonal is rated $\sqrt{2}$. The state of unstable combustion could be designated as a burst of the flame contour length, as shown in Fig. 4.

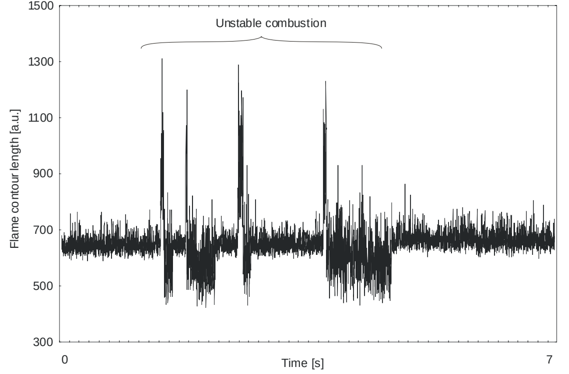


Fig. 4. Flame contour length for stable and unstable combustion.

The influence of the aforementioned combustion parameters on a flame contour, as expressed by the Fourier descriptors, was also taken into consideration. However, it requires that the flame region should be single so as to obtain a closed contour [5]. It was assumed that the starting point of a given flame boundary was its left upper pixel and ordered in clockwise direction. Assuming that the flame boundary with N pixels is represented by a complex vector:

$$\mathbf{B}=\begin{pmatrix} x_1+\mathrm{j}y_1 \\ x_2+\mathrm{j}y_2 \\ \vdots \\ x_N+\mathrm{j}y_N \end{pmatrix}, \qquad (1)$$

where x_l, y_l denotes l-th flame boundary pixel coordinates, the m-th Fourier descriptor is given as:

$$F_m=\sum_{k=0}^{N-1}\mathbf{B}_k\,\mathrm{e}^{-\frac{\mathrm{j}2\pi km}{N}}. \qquad (2)$$

It was assumed that each flame contour was described by 400 Fourier descriptors. A “zero frequency” image descriptor represents the centre of gravity and points to the translation of a given contour in an image plane.

Only modules of the Fourier descriptors A_m, were taken into consideration, $A_m=|F_m|$. An exemplary amplitude spectrum variability in time domain is presented in Fig. 5.

Fourier descriptors corresponding to low-frequencies were centered according to Matlab `fftshift` function. Thus, a “zero frequency” descriptor corresponds to F_{201}. The Fourier descriptor corresponding to lower frequencies are placed symmetrically around F_{201}, as shown in Fig. 5. Taking the energy of Fourier descriptors into consideration, one can notice that almost all energy is contained within low-frequency components.

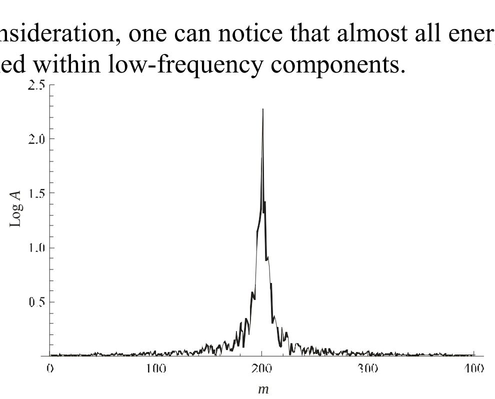
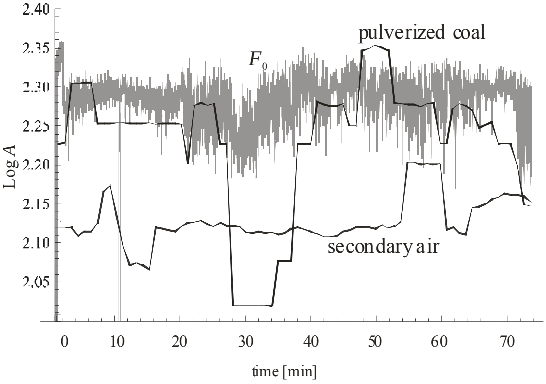


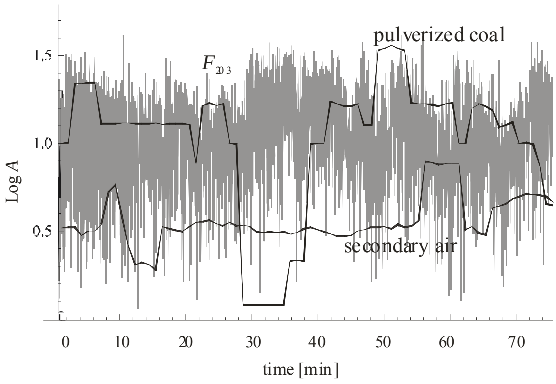
Fig. 5. Fourier descriptors for an exemplary flame contour .

A variety of the selected Fourier descriptor in the time domain is presented in fig 6, together with secondary air and pulverized coal flow. Primary air is used as a coal transporting medium and not for regulation purposes, thus it was omitted.

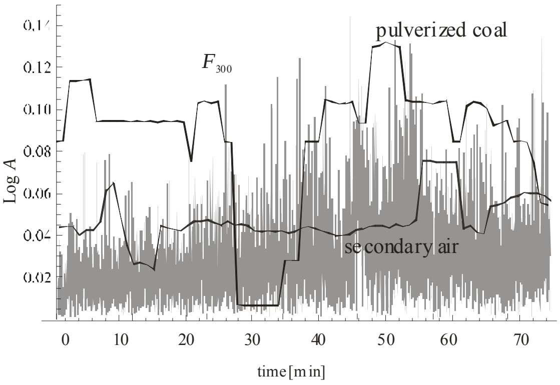
In Fig.6a, one can notice the dependence of F_0 amplitude – A_0 on coal flow, especially its drops. Dropping coal flow also results in dropping A_0, whereas a rise in its value causes a transient change of A_0. Such a dependence could not be observed for amplitude of an example “low frequency” Fourier descriptor – F_{203}, as shown in Fig.6c.



a)



b)



c)

Fig. 6. Amplitude variability of Fourier descriptors in the time domain for: a)“zero frequency” component F_0, b) “low frequency” component – F_{203}, c)“high frequency” component F_{300}.

Changes in the air-fuel ratio result in its variability but its influence is not clear. The dependence of “high frequency” components, shown as an example of A_{300} in Fig.6c, for air and coal flows, is quite different than in the previously discussed cases. The short combustion instability that occurred after rising coal flow in 48 min. of the experiment, is pointed out by the rise in A_{300}.

Unstable combustion of pulverized coal can be detected using the presented geometric parameters of flame images. Its determination generally does not require high processing capacity, for acquisition speed and image resolution values used during combustion test. They can be calculated in real-time. However, estimating air or coal flows would be difficult.

Analyzing the flame contour gives far more information and could be helpful in both combustion instability detection and air/fuel ratio estimation.

It should be pointed out that only a part of the flame image could be captured. The obtained results greatly depend on camera positioning and the combustion set-up.

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