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Detection of biomass-coal unstable combustion using frequency analysis of image series

Streszczenie. *Artykuł przedstawia problem oceny procesu spalania mieszaniny pyłu węglowego i biomasy ze zwróceniem szczególnej uwagi na jego stabilność. W trakcie przeprowadzonego eksperymentu zmieniano istotne parametry wejściowe stanowiska jak przepływy powietrza wtórnego oraz wydatek węgla. Zarejestrowane przez szybką kamerę sekwencje obrazów podzielono na jednakowe obszary uzyskując szeregi czasowe, które poddane zostały analizie częstotliwościowej w celu określenia ich przydatności w diagnostyce procesu spalania. (**Detekcja niestabilnego spalania mieszaniny biomasy i węgla na podstawie analizy częstotliwościowej sekwencji obrazów**).*

Abstract. *Biomass co-combustion with coal is one of the cheapest ways of utilizing renewable fuel. However it results negative side-effects The article presents experimental set-up and frequency analysis that was done for the captured image series. Every image was partitioned into separately analyzed parts of equal size. The most sensitive flame area to possible combustion instabilities is pointed out on the basis of frequency analysis of times series obtained from each part of flame image series.*

Słowa kluczowe: Współspalanie biomasy, przetwarzanie obrazu, transformata Fouriera.
Keywords: Biomass co-combustion, image processing, Fourier transform.

Introduction

Biomass co-combustion with coal is one of the means of utilizing renewable energy. Its main advantage is possibility of using existing combustion facilities after appropriate adaptations. Combustion of biomass-coal mixture can occur in unstable way, especially due to variable properties of biomass components and different weight density than that of the coal. Additionally, problems arise optimizing the operation of an individual burner for there are no methods of direct measurement of amount the coal dust supplied to the burner, as well as primary air. Usually, these parameters evaluated through indirect measurements of e.g. load of the mill and fan delivery, so the precision of such measurements is low [1]. What is more, fossil fuel depletion forces the use of renewable fuels, such as biomass. In the existing coal-fired power stations, biomass is milled and burned simultaneously with coal. However, low-emission combustion techniques as well as biomass co-combustion have negative side effects on combustion installations – increased corrosion and boiler slagging [2-4].

Unstable combustion is defined as immunity to slight disturbances, that provides the flame to return to its previous shape after their retreating. The other definition of stability means a set of conditions, under which flame is still present. Their exceeding leads to flameout [4, 5]. In practice, it is important to detect a state of unstable combustion, not only because of explosion threat, but for minimizing emission of harmful combustion products to atmosphere as well as losses due to incomplete combustion.

The mentioned above reasons impose using of a proper monitoring system [2]. As the radiation emitted by flame is vital source of information for pending combustion process, optical-based systems are commonly used [3]. Most of them utilize frequency analysis of flame flickering signals obtained by various optical probes. They should be mounted near burner being monitored. However, the probe installation may encounter serious obstacles for the boiler construction limitations. On the other hand, a care should be taken with optical probe mounting for it should provide signals as sensitive as possible to changing state of the combustion process. In order to simplify choosing flame the most sensitive area, a system consisting of high speed digital camera can be utilized [6, 7]. On the other hand, it provides simultaneous monitoring within arbitrary defined flame areas.

Vision systems for combustion monitoring allow to determine various parameters of flame such as geometric (e.g. size, position), radiation properties (e.g. emission spectrum, irradiation distribution), flame flicker frequency, etc. Information obtained from vision combustion monitoring systems combined with information of exhaust gases composition and fuel chemical and physical properties could lead to optimize the combustion process

Laboratory combustion facility

Combustion tests were done in a 0.5 $\mathrm{MW_{th}}$ research facility, enabling scaled down (10:1) combustion conditions. The main part is a cylindrical combustion chamber, 0.7 m in diameter and 2.5 m long. A model of low-NOx swirl burner about 0.1 m in diameter is mounted at the front wall. The stand is equipped with all necessary supply systems: primary and secondary air, coal, and oil. Pulverized coal for combustion is prepared in advance and dumped into the coal feeder bunker. Biomass in a form of wood chips is mixed with coal after in the feeder.

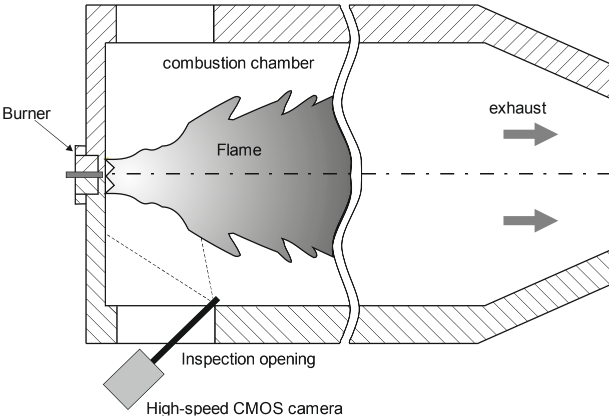

Fig.1. Combustion chamber with camera mounting

The combustion chamber has two lateral inspection openings on both sides, which enable image acquisition. A high-speed camera with CMOS area scan sensor was placed near burner's nozzle, as shown in fig.1. A 0.7m borescope was used in order to transmit flame images. The camera was capable to acquire 500 frames per second. The optical system was cooled with water. Additionally purging air was used to avoid dustiness of optical parts.

More details describing the test facility have been presented in [8].

Combustion tests

Combustion tests consisted in initial warming up the combustion chamber with oil burner, that lasts about 10 minutes. When temperature inside the combustion chamber reached the appropriate level (~200°C), coal feeder was started and coal-air mixture was delivered to the burner. After about 10 min of simultaneous work of oil and coal burners, oil burner was switched-off. Next, both coal and air flows were changed in time. Primary air is used mainly for delivering pulverized coal to burner nozzle, while secondary and tertiary airs are used mainly for regulation purposes. The secondary air is inserted closer to burner axis as opposed to the tertiary one. Input parameters, i.e. coal and air flows were changed several times during the tests, so as to bring different combustion states - stable and unstable. Example change of air/fuel ratio is shown in figure 2. Keeping fuel (coal with 10% of wooden chips added) flow constant, initially air flow was decreased (15:35:00 - 15:36:50) and increased afterwards. It resulted in observed flame instability with decrease of NO concentration in flue gases.

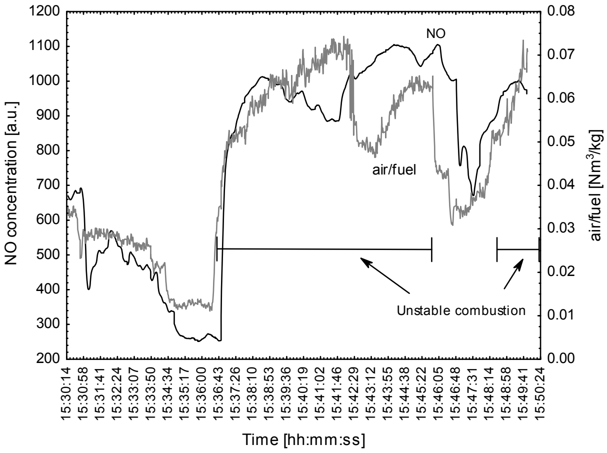

Fig.2. Coal and air flows variations during an example combustion test

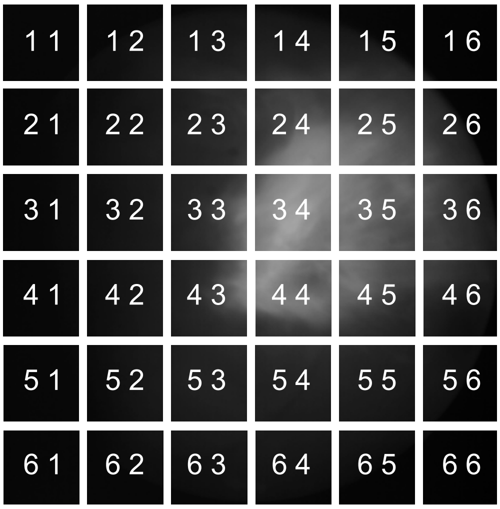

Fig.3. Coal and air flows variations during an example combustion test

The way, camera was mounted has enabled observing only part of flame that was placed close to burner nozzle, in spite of relatively large numerical aperture of the borescope. Previous researches with fiber-optic, multichannel flame monitoring system have shown, that this is the most sensitive flame region to changes of input parameters of the burner [9].

Every image of 384×384 pixels was splitted into 36 square parts, every of 64×64 pixels, as shown in figure 3. Within the every part of image, flame intensity was averaged. Thus, 36 time series were obtained, corresponding to flame intensity variation for different flame regions. Example time series obtained for selected regions are presented on figure 4 and 5. It could be noticed, that stronger signals are observed for image parts marked on figure 4, and 5 as 43, 44, 34 and are obtained from area placed near burner nozzle. On the other side, some image parts as e.g. 41 is located outside flame area and could be omitted in further analyses.

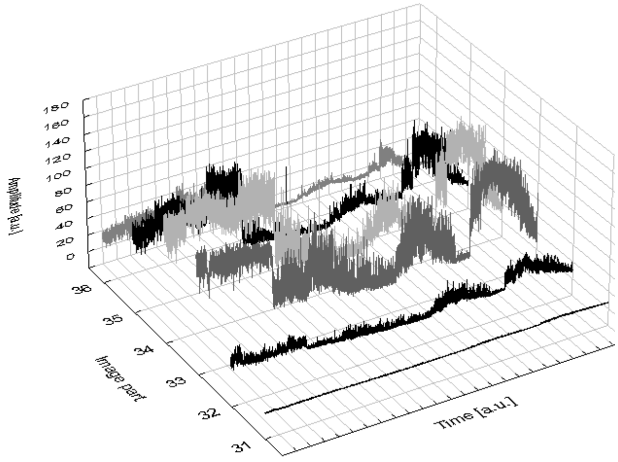

Fig.4. Time series obtained for image parts located in the third row on fig. 3

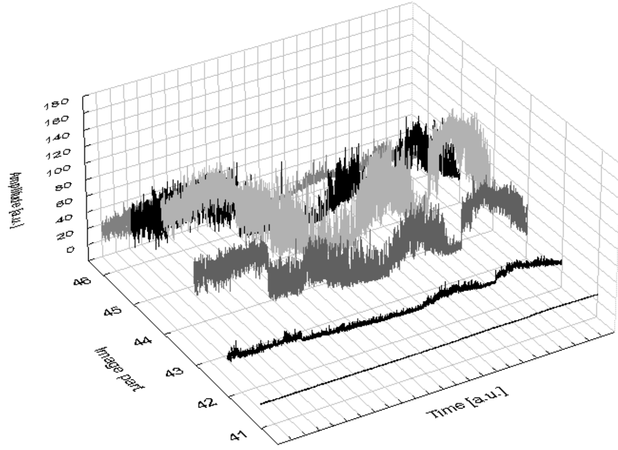

Fig.5. Time series obtained for example image parts located in the fourth row on fig. 3

For the image acquisition rate was 150 frames per second, the maximum frequency of flame flicker, on the basis of Nyquist theorem was 75Hz. Frequency analysis was performed on the signals corresponding to the particular image parts. Short-time Fourier transform was used with Hamming window.

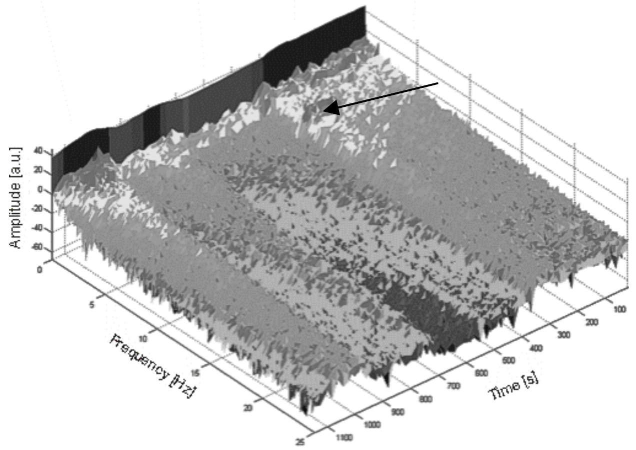

Fig.6. Spectrogram of time series obtained for image part marked as 34

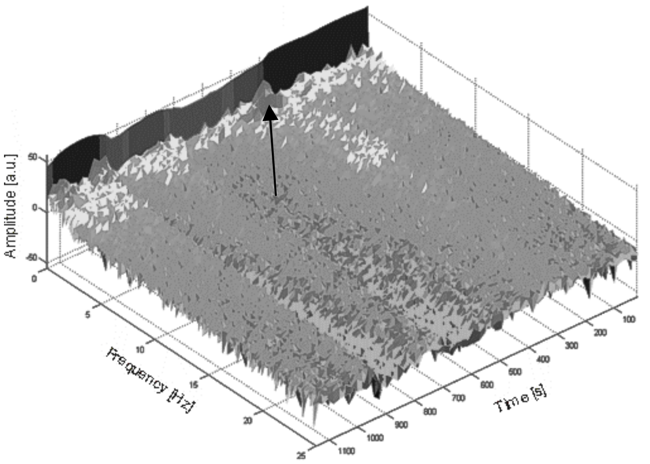

Fig.7. Spectrogram of time series obtained for image part marked as 43

Results of time-frequency analysis for signals obtained from image parts marked on Fig. 3 as 34 and 43 are shown on Fig. 5 and 6, respectively. A window of 4096 points was used resulting in frequency resolution of 0,024Hz.

The spectrograms shown ion Fig. 6 and 7 reflect strong representation of relatively low frequencies ranging from 0 to a few Hz. The spectrograms obtained differ as they reflect variable flame flicker for the image parts being examinated. Decreasing air/fuel ratio from 15:35:00 to 15:36:50 results in frequency peak around 4Hz, that could be seen in Fig. 5. On the other side, rapid increase in air/fuel ratio, when the state of unstable combustion occurs, results in presence of 1Hz peak in Fig. 6 and subsequent decrease of frequencies above 5Hz in Fig. 5.

Conclusions

High speed video camera equipped with a borescope can be used as a multichannel flame monitoring system, with user-defined flame areas. Frequency patterns differ for case of stable and unstable combustion. Flame zones, located near burner's outlet a reported to be the most appropriate in detection of unstable combustion. The characteristic frequencies should be determined individually for each burner after initial tests.

Comparing the presented system with the one containing fiber-optic multichannel fiber optic probe, it is more versatile, especially when wide-angle borescope or lens would be applied. Flame areas being inspected can be of any defined shape. Vision system equipped with high-speed camera may be applied in combustion diagnostics based on flame flicker analysis.

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