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Assessment of biomass-coal co-combustion on the basis of flame image

Streszczenie. *Artykuł przedstawia sposób oceny procesu spalania mieszaniny pyłu węglowego i biomasy wykorzystujący informację zawartą w zmianach pola powierzchni płomienia wyznaczonych dla sekwencji obrazów. Obrazy płomienia rejestrowane były przez odpowiedni układ wyposażony w kamerę CMOS i boroskop, pozwalający na obserwację strefy w pobliżu palnika pod kątem 45° do osi płomienia. W tym celu przeprowadzono szereg testów spalania na stanowisku laboratoryjnym w których w sposób niezależny zmieniano moc cieplną oraz współczynnik nadmiary powietrza dla mieszanin węgla i biomasy o zawartość 10% i 20%.*

Abstract. *The article presents the way of assessment of biomass coal mixture combustion using information in a form of flame area changes determined for image sequences. The images were captured by a dedicated visual system equipped with CMOS camera and a borescope that enabled observing flame zone located near burner at 45° to flame axis. Several laboratory combustion experiments were carried out when thermal power and excess air coefficient were set independently for fuel mixtures with biomass content of 10% and 20%.* ***(Ocena stanu procesu spalania mieszanin pyłu węglowego I biomasy na podstawie obrazu płomienia).***

Słowa kluczowe: Współspalanie biomasy, przetwarzanie obrazu.
Keywords: Biomass cofiring, image processing.

Introduction

Renewable fuels as are considered as one of the main ways of reducing greenhouse-gas emissions, especially CO_2. Cofiring of coal and biomass is one the easiest and cheapest way of using renewable energy source for the possibility of using existing combustion facilities. Biomass-coal co-combustion can be quickly adapted in large-scale systems. Combustion process is stabilized by presence of coal in fuel mixture. Moreover, substituting biomass for coal reduces SO_2 emissions as well as NOx due to the low sulfur and low nitrogen contents of biomass [1]. Comparing to pure coal, biomass is generally more reactive having higher volatile matter content [1–2].

On the other side, biomass-coal co-firing has significant drawbacks. Biomass contain less carbon and more oxygen than coal, that results in lower heating value. High moisture as well as ash content can be a reason of possible combustion stability problem. On the other side, higher chlorine contents rise corrosion rate. The melting point of the ash can be low. It causes increased slagging and fouling of combustor surfaces that reduce heat transfer and result in corrosion and erosion problems. Comparing to coal, biomass has lower density and friability that results in possible stratification of fuel mixture contents during its conveyance to burners. What is more, both physical and chemical biomass parameters of biomass are unsteady in time.

All the mentioned above factors affect the boiler operation and make combustion process course difficult to lead. Thus, application of a proper monitoring system is essential to ensure proper operational conditions.

Flame, being the main reaction zone of a combustion process is the quickest source of information. The measurable physical attributes of a flame, such as magnitude and shape of luminous area, flicker frequency provide vital information of the combustion process. Optical sensing methods conjoined with advanced signal analysis allow relatively cheap, non-intrusive characterization of combustion process, that can be held in real-time [3]. Analysis of flame images allows to determine various parameters of flame such as geometric (e.g. size, position), radiation properties (e.g. emission spectrum, irradiation distribution) [4–9].

This paper presents investigation of flame area using imaging techniques obtained for different states of combustion process. Laboratory tests were carried out a few settings of secondary air flow and thermal power for two different coal-biomass mixtures.

Laboratory combustion facility

Combustion tests were done in a 0.5 MW_{th} (megawatt of thermal) research facility, enabling scaled down (10:1) combustion conditions. The main part is a cylindrical combustion chamber of 0.7 m in diameter and 2.5 m long. A low-NOx swirl burner about 0.1 m in diameter is mounted horizontally at the front wall. The stand is equipped with all the 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 straw is mixed with coal after passing through the feeder.

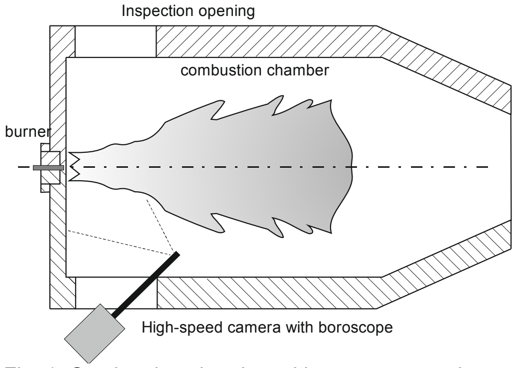

Fig. 1. Combustion chamber with camera mounting

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. Flame images were transferred from the interior of the combustion chamber through a 0.7 m borescope. The camera was capable to acquire up to 500 frames per second at its full resolution (1280×1024 pixels). The optical system was cooled with water jacket. Additionally, purging air was used to avoid dustiness of optical parts.

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- biomass mixture was delivered to the burner. After reaching the proper temperature level, the oil was switched off. The fuel mixture was delivered by, so called, primary air. Excess air coefficient was determined through secondary air flow, whereas primary air was used only for fuel feeding.

Combustion testes were done for different combinations (variants) of the combustion facility, where thermal power (P_{th}) and excess air coefficient (λ) were set independently for known biomass content, where λ is defined as quotient the mass of air to combust 1kg of fuel to mass of stoichiometric air. The exact values of thermal power and excess air coefficient are collected in Table 1.

Table 1. The variants of biomass-coal combustion tests

Variant #	1	2	3	4	5	6	7	8	9
P_{th} (kW)	250	250	250	300	300	300	400	400	400
λ	0.75	0.65	0.85	0.75	0.65	0.85	0.75	0.65	0.85

The tests were performed for two fuel mixtures containing 10% and 20% of biomass (straw) respectively. During the combustion tests, physical properties of biomass (particle size, inherent moisture, etc.) remained unchanged as well as the all image acquisition parameters, such as camera gain, frame rate, exposure time. Flame images were captured for every variant of the combustion facility and different fuels mixtures. The images were converted to 8-bit grayscale, thus pixel amplitude was ranging from 0 to 255. Flame area within each frame of the acquired image sequence was determined on the basis of pixel amplitude. Such an assumption was possible to accept for the flame was far brighter than any other objects within field of view of the borescope applied. Flame area was defined as a sum of all the pixels that were contained within the flame region.

Experiment results

Changes of flame area that were obtained for fuel mixtures with 10% and 20% content of biomass obtained for different values of thermal power and excess air coefficient are presented in Fig. 2 and 3, respectively.

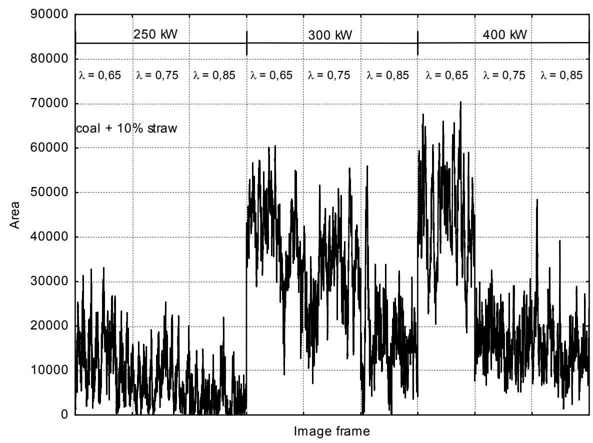

Fig. 2. Flame area obtained for different states of combustion process – coal with 10% of biomass (straw).

Every combustion state defined by set of constant values of P_{th}, λ, and biomass content was represented by 2000 images. Generally, raise of thermal power of combustion facility cause increase of flame area, as shown in Fig. 2 and 3. It could be also observed in Fig. 4–7 for mean values of flame areas.

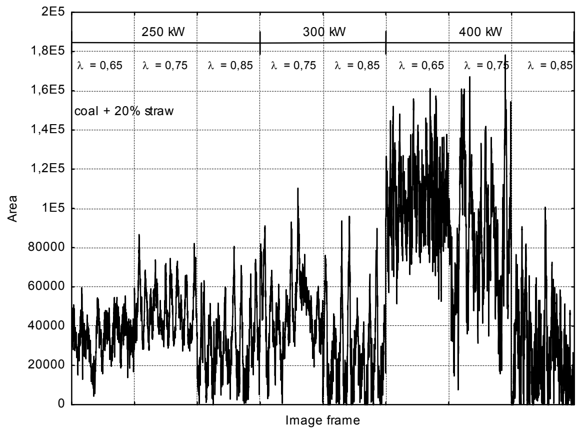

Fig. 3. Flame area obtained for different states of combustion process - coal with 20% of biomass (straw).

Another important factor is flame area variability calculated for each combustion state. It is marked in Fig 4–7 as double standard deviation (SD) of flame area.

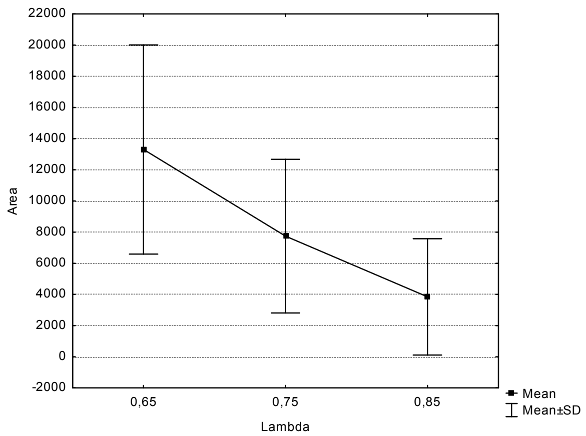

Fig. 4. Mean values of flame area for different excess air coefficients (lambda) obtained for coal with 10% of biomass added for P_{th} = 250 kW.

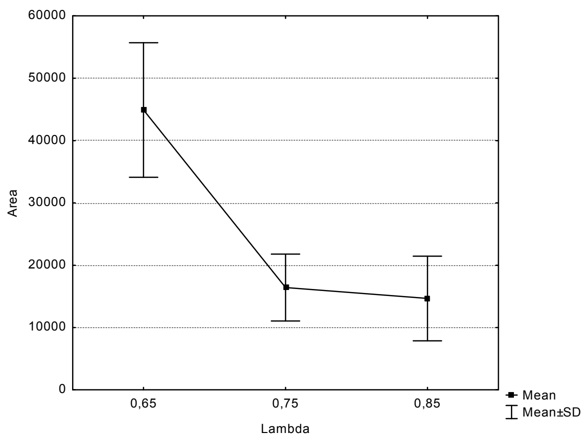

Fig. 5. Mean values of flame area for different excess air coefficients (lambda) obtained for coal with 10% of biomass added for P_{th} = 400 kW.

Amount of excess air coefficient greatly affects combustion process. However, mean value of flame area has different dependences on λ for different values of thermal power. For P_{th} = 400kW flame area decreases when excess air coefficient increases for fuel mixtures with 10% and 20% of biomass (Fig. 5 and Fig. 7), whereas for P_{th} = 250 kW they show different kind of dependence (Fig. 4 and Fig. 6).

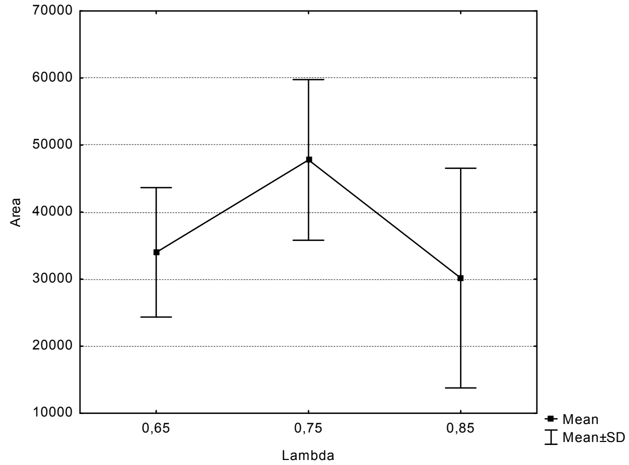

Fig. 6. Mean values of flame area for different excess air coefficients (lambda) obtained for coal with 20% of biomass added for P_{th} = 250 kW.

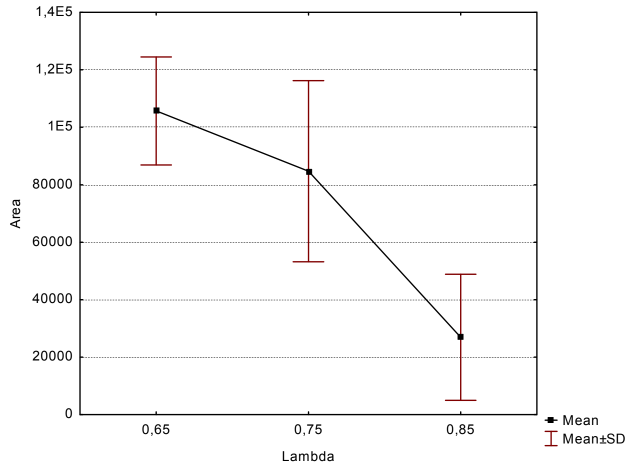

Fig. 7. Mean values of flame area for different excess air coefficients (lambda) obtained for coal with 20% of biomass added for P_{th} = 400 kW

Comparing the mean values of flame area for the same excess air coefficient it could be observed that flame area is larger for fuels mixtures with higher biomass content. This is due to the fact that generally biomass contain more volatile contents comparing to coal.

Flame area also points to possible unstable combustion that were reported for higher excess air coefficients regardless the thermal power (Fig. 2 and Fig. 3) and observed as sudden changes of the discussed parameter as well as its values equal to zero. Unstable combustion is the more serious problem the more biomass is added (Fig. 3).

Conclusions

It should be noted, that the flame area strongly depends on the way the flame area was defined. Usually, during laboratory tests camera is mounted perpendicularly to burner axis [4–9]. Thus distance between burner and flame ignition point [4,7] could be estimated as well as spread angle of the flame that provides vital information of combustion process state. However in practice, in case of existing full-scale power boilers it is nearly impossible to mount a camera close to a burner, perpendicularly to its axis for it would usually require serious interference in boiler's shield. That is why, alternative camera set-up was examined.

Flame area by many is used as one of main pointers of combustion process state [4–9]. Another important factor is it can be easily estimated in a series of images, thus it could be used in real-time applications regardless the place of camera mounting. It should be underlined that the factors investigated that were used for combustion process assessment strongly depend on burner type and size of combustion chamber and thus cannot be used directly in full scale combustion facilities.

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