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BIOMASS-COAL COMBUSTION CHARACTERIZATION BASED ON SERIES OF FLAME IMAGES

The article presents the assessment method of biomass coal mixture combustion using information in a form of flame area parameters obtained for each frame. The images were captured by a dedicated visual system equipped with high-speed 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%.

Keywords: *biomass combustion, image processing.*

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ДОСЛІДЖЕННЯ ХАРАКТЕРИСТИК СПАЛЮВАННЯ БІОМАСИ І ВУГІЛЛЯ НА ОСНОВІ СЕРІЇ ЗОБРАЖЕНЬ ПОЛУМ'Я

У статті представлено метод оцінювання згорання суміші біомаси і вугілля з використанням інформації у вигляді деяких параметрів полум'я, отриманих для кожного кадру. Зображення було отримано за допомогою спеціально розробленої системи візуального спостереження, оснащеною високошвидкісною CMOS-камерою і бороскопом, яка дала можливість спостереження за зоною полум'я, розташованої біля пальника під кутом 45° до осі полум'я. Було проведено декілька лабораторних експериментів згорання при незалежних показниках теплової потужності і коефіцієнта надлишку повітря для паливних сумішей з біомасою вмістом 10% і 20%.

Ключові слова: *згорання біомаси, обробка зображень.*

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ИССЛЕДОВАНИЕ ХАРАКТЕРИСТИК СЖИГАНИЯ БИОМАССЫ И УГЛЯ НА ОСНОВЕ СЕРИИ ИЗОБРАЖЕНИЙ ПЛАМЕНИ

В статье представлен метод оценки сгорания смеси биомассы и угля с использованием информации в виде некоторых параметров пламени, полученных для каждого кадра. Изображения были получены с помощью специально разработанной системы визуального наблюдения, оснащенной высокоскоростной CMOS-камерой и бороскопом, которые дали возможность наблюдения зоны пламени, расположенной возле горелки под углом 45° к оси пламени. Были проведены несколько лабораторных экспериментов сгорания при независимых показателях тепловой мощности и коэффициента избытка воздуха для топливных смесей с биомассой содержанием 10% и 20%.

Ключевые слова: *сгорание биомассы, обработка изображений.*

Introduction. Renewable fuels as are considered as one of the most important means 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 pres-

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ence 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]. Another advantage of biomass co-firing is higher volatile contents and high reactivity of both fuel and resulting char [1,2].

On the other side, biomass-coal co-firing has significant drawbacks. Comparing to coal, biomass contains less carbon and more oxygen, that results in lower heating value. High moisture as well as ash content can be a reason of possible combustion stability problem. Higher chlorine contents rise corrosion rate. Lower melting point of the ash 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 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 provide 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 real time [3]. Analysis of flame images allows determining various parameters of flame such as geometric (e.g., size, position), radiation properties (e.g., emission spectrum, irradiation distribution) [4-10].

a)

b)

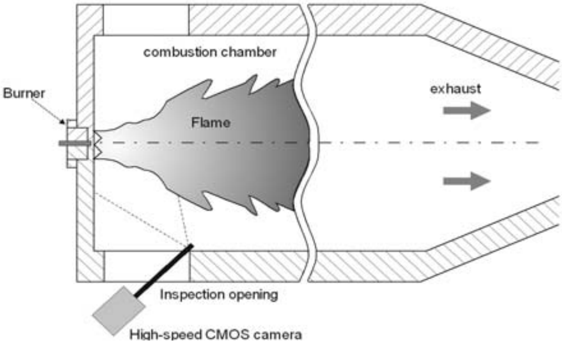


Figure 1. **General view of combustion facility — a) with a sketch of camera mounting**

Laboratory combustion facility. The combustion tests were done in a 0.5 MW_{th} (megawatt of thermal) research facility, enabling scaled down (10:1) combustion conditions with swirl burner. Its main part is a combustion chamber of cylindrical shape, 0.7 m in diameter and 2.5 m long. A low-NOx 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.

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 0.7m 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 elements of the probe.

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 the so-called primary air. Excess air coefficient was determined through secondary air flow, whereas primary air was used only for fuel feeding.

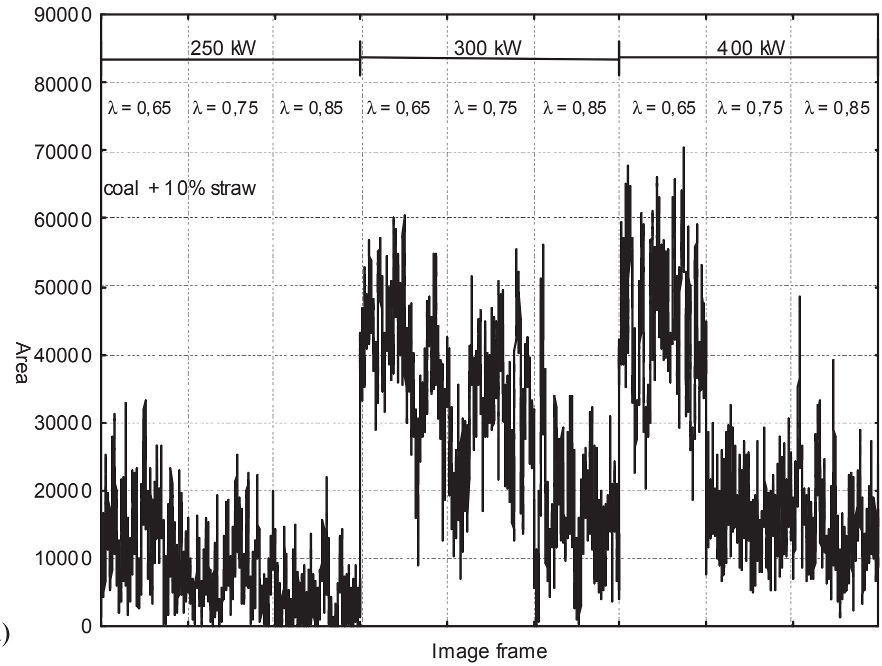
Combustion testes were done for different combinations (variants) of the combustion facility, where thermal power (Pth) and excess air coefficient (λ) were set independently for known biomass content, where λ is defined as quotient the mass of air to combust 1kg of fuel to mass of stoichiometric air.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

Table 1. **The variants of biomass-coal combustion tests**

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. Coordinates of flame area center (x, y), calculated as the mean value of the line or column coordinates, respectively, of all flame area pixels. Flame contour length was defined as a sum of all boundary pixels, assuming that the distance between two neighboring contour points parallel to the coordinate axes is rated 1, while the distance in the diagonal is rated $\sqrt{2}$.

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. Every combustion state defined by set of constant values of P_{th}, λ, and biomass content was represented by 2000 images.



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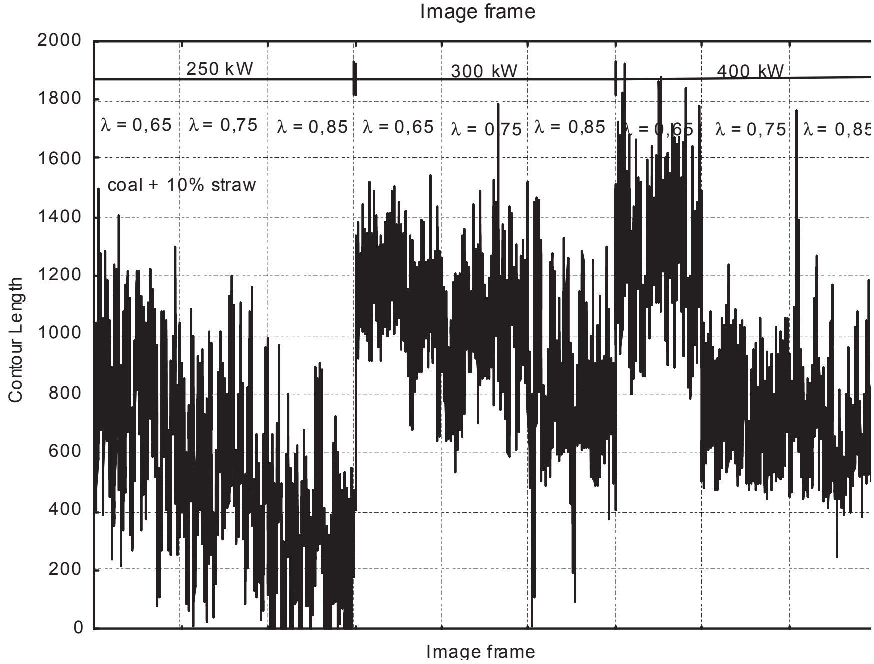

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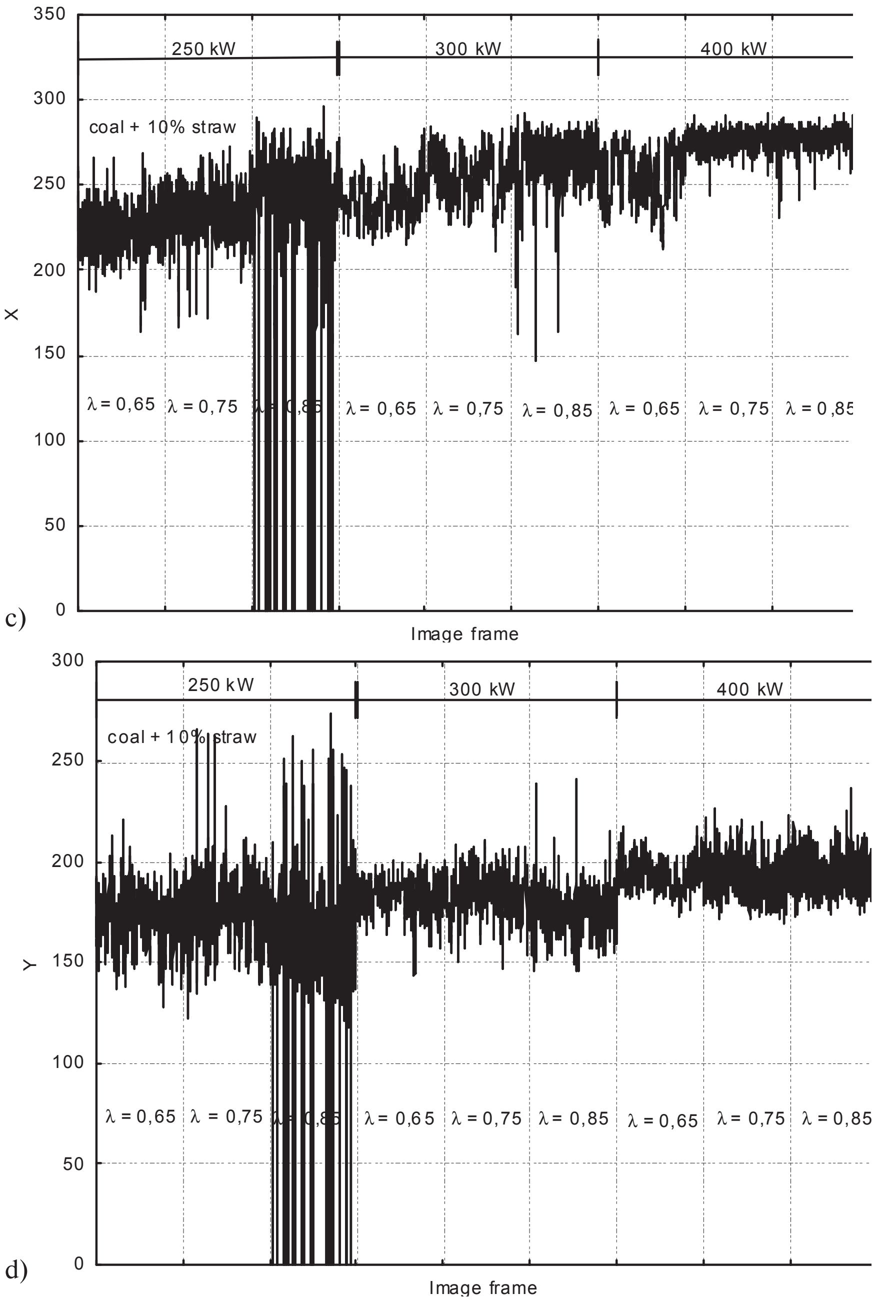
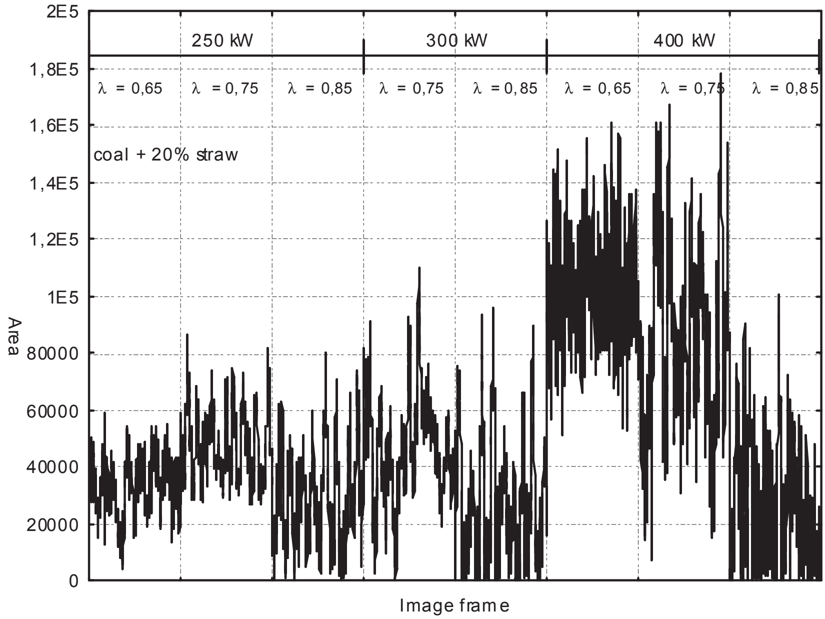


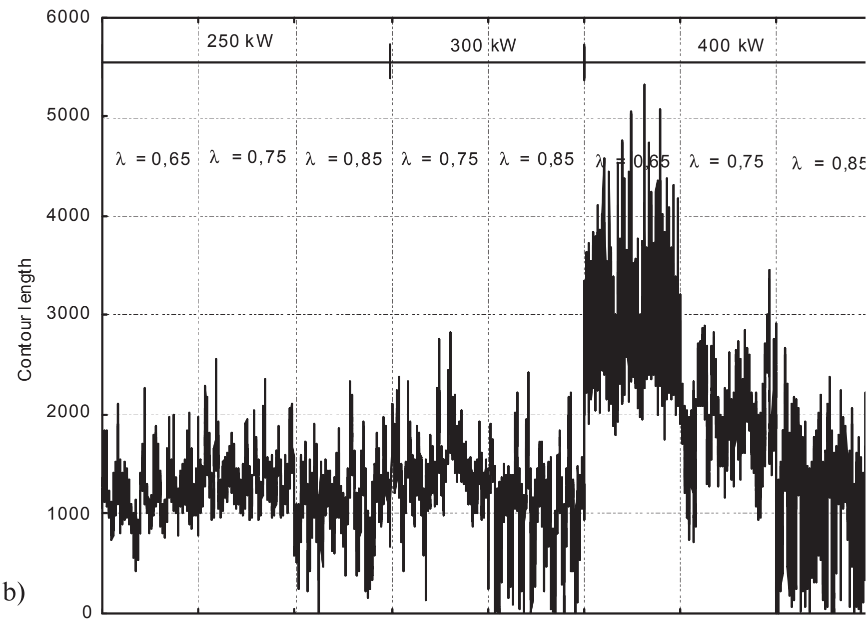
Figure 2. **Flame area (a), contour length (b) and coordinates of flame area center (c, d) obtained for different states of combustion process — coal with 10% content of biomass**

Generally, raise of thermal power of combustion facility cause increasing of flame area, as shown in Fig. 2a and 3a. The same dependence could be observed in Fig. 4-7 also for mean values of flame area and flame contour length. Rise of thermal load also affect coordinates of flame area center, especially the x-coordinate for coal with 10% of biomass only indicating that the distance between flame front and burner nozzle increases (Fig 2c). For the other fuel mixture tested, flame position was more stable (Fig. 3c, 3d).

Low values of flame area and contour length as well as sudden drops of coordinates of flame center area observed for P_{th} =250kW and λ = 0.85 points to stability problems, that occurred during combustion tests.



a)



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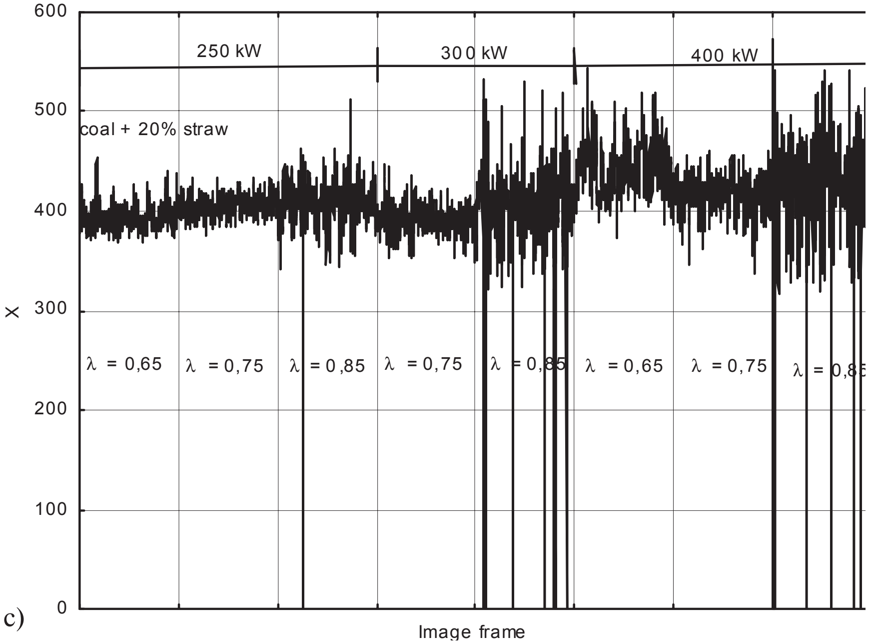
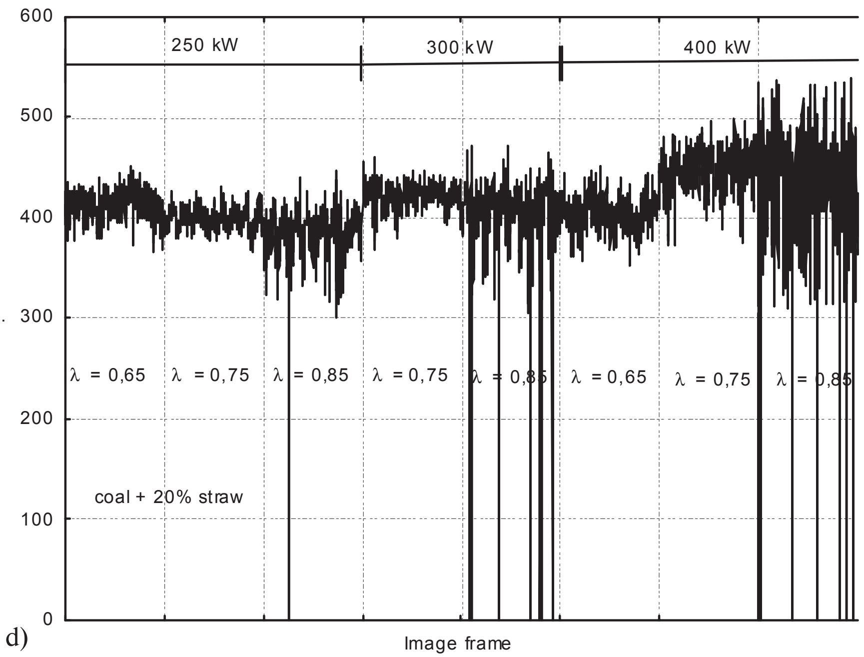


c)



d)

Figure 3. **Flame area (a), contour length (b) and coordinates of flame area center (c, d) obtained for different states of combustion process — coal with 20% content of biomass**

Another important factor is variability of the flame parameters discussed, that were calculated for each combustion state. It is marked in Fig 4-7 as double standard deviation (SD).

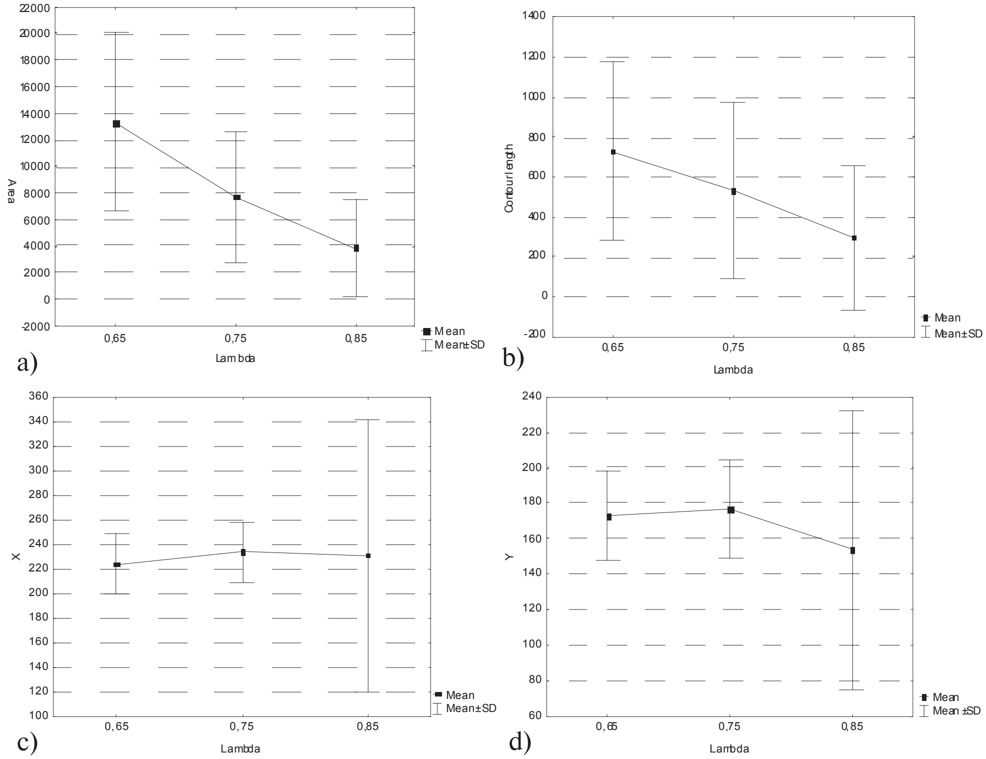


Figure 4. **Mean values of flame area (a), contour length (b) and coordinates of flame area center for different excess air coefficients (lambda) obtained for coal with 10% of biomass added for P_{th} = 250kW.**

Amount of excess air coefficient greatly affects the 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.5a and 7a), whereas for Pth = 250kW, the other type of dependence can be observed (Fig.4a and 6a). Variability of flame contour length is almost the same as in the case of flame area.

Changes of flame centre position is different for the examined variants. For biomass content of 20%, standard deviation of the discussed parameter is greater, especialy for greater λ and thermal power value (Fig. 5c, 7c,).

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 has more volatile contents comparing to coal.

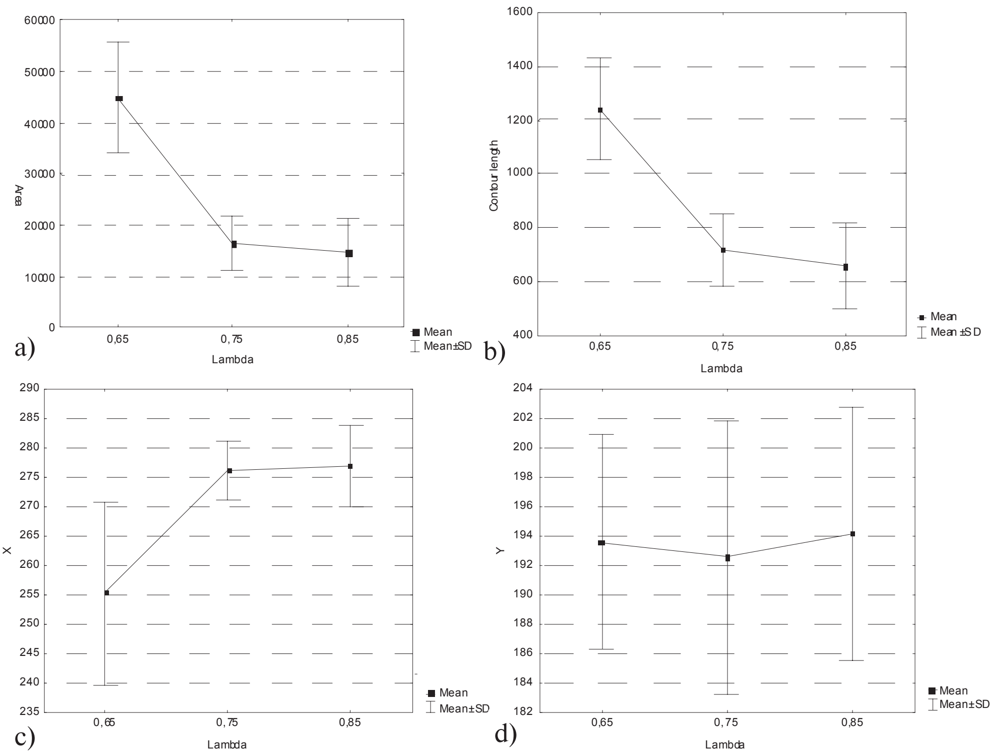
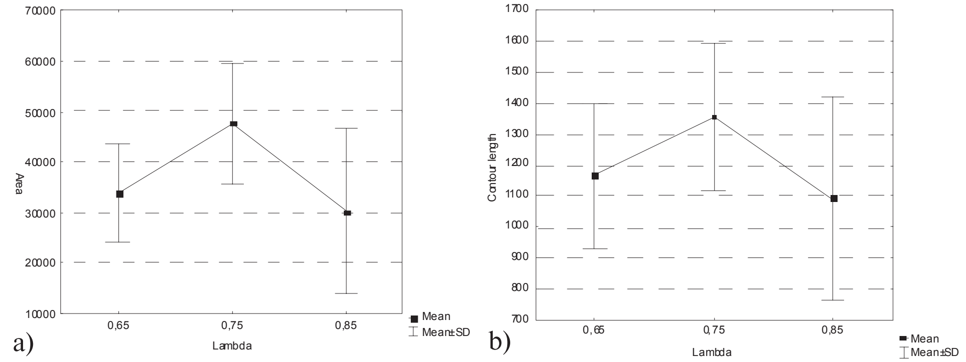


Figure 5. **Mean values of flame area (a), contour length (b) and coordinates of flame area center for different excess air coefficients (lambda) obtained for coal with 10% of biomass added for P_{th} = 400kW.**

Flame area, contour length and flame centre coordinates also point to possible unstable combustion that were reported for higher excess air coefficients regardless the thermal power (Fig.2 and 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).



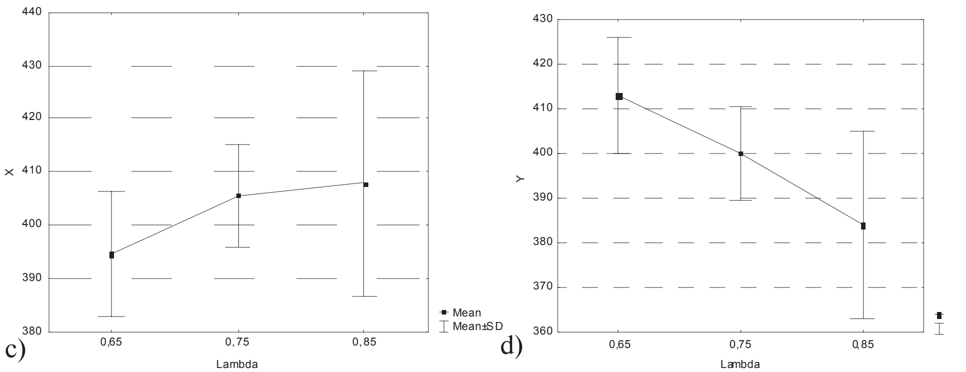


Figure 6. **Mean values of flame area (a), contour length (b) and coordinates of flame area center for different excess air coefficients (lambda) obtained for coal with 20% of biomass added for P_{th} = 250kW.**

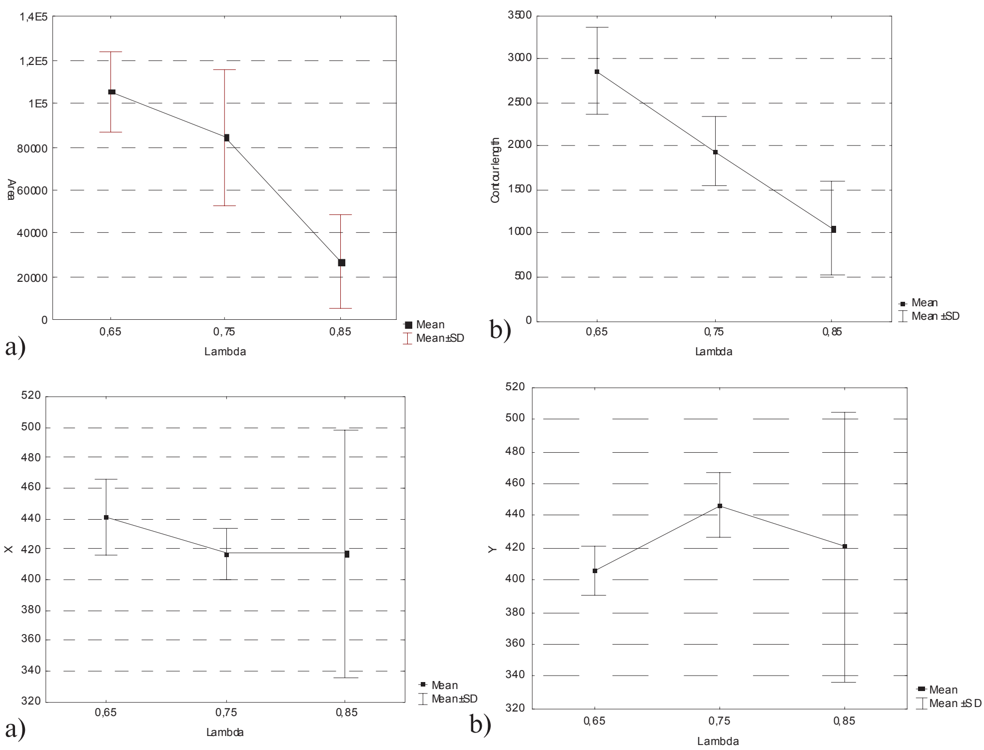


Figure 7. **Mean values of flame area (a), contour length (b) and coordinates of flame area center for different excess air coefficients (lambda) obtained for coal with 20% of biomass added for P_{th} = 400kW**

Conclusion. It is worth noting that flame area and its contour length strongly depend 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 on the combustion process. However, in practice, in the case of 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 was a reason for testing an alternative camera set-up.

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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