Andrzej KOTYRA[1], Waldemar WÓJCIK[1], Konrad GROMASZEK[1] ,Gulmira BAZIL[2]

Lublin University of Technology (1), Kazakh National Technical University after K.I. Satpaev (2)

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Application of flame image series analysis in estimation of biomass and coal combustion operating point

Abstract. *The paper considers access of combustion process of pulverized coal and biomass blend using analysis of flame images. Several flame image parameters were examined as pointers of one of the basic combustion process input parameters as air and fuel flow rate. Image parameters like greyscale area region, coordinates of centre of gravity and flame area contour length were averaged in a fixed time span. The aim of investigations was assessing ability to determine air and fuel flow rates on the basis of the mentioned image parameters.*

Streszczenie. *W artykule ocenę procesu współspalania biomasy i węgla z wykorzystaniem przetwarzania obrazu. Rozpatrywano kilka parametrów obrazu jako wskaźniki najważniejszych parametrów wejściowych procesu spalania jak wydatki paliwa i powietrza. Parametry obrazu, jak powierzchnia obszaru w skali szarości, współrzędne środka ciężkości i długość konturu były uśredniane w ustalonym oknie czasowym. Celem badań była ocena możliwości określenia wydatków paliwa i powietrza na podstawie wspomnianych parametrów obrazu (**Wykorzystanie analizy sekwencji obrazów do estymacji punktu pracy procesu współspalania biomasy z węglem**).*

Keywords: biomass cofiring, flame, image processing.
Słowa kluczowe: współspalanie biomasy, płomień, przetwarzanie obrazów.

Introduction

Nowadays, climate protection becomes more and more serious problem. Renewable fuels are considered as one of the main ways of reducing greenhouse-gas emissions, especially CO_2 for it is absorbed during plant growth and released during combustion. Hence it does not contribute to the greenhouse effect.

The European Union have expressed policy by endorsement a commitment of individual countries to reduce greenhouse gases by at least 20% by 2020, comparing to the 1990 level. The package, known as “3x20”, includes CO2 emissions reduction by 20%, energy consumption drop by 20% and increase in the renewable energy share the EU up to 20% by the year 2020. Achieving these objectives of the climate and energy package requires development and implementation of low carbon technologies.

Biomass is one of the renewable fuels of the greatest significance. It was reported that biomass provides 14% of the world’s energy demands [1]. The term biomass is related to variety of organic substances, including wood, agricultural wastes, short-rotation herbaceous species, grass, wood wastes, municipal solid wastes, aquatic plants as well as animal wastes.

Biomass can be fired directly or co-fired with other solid fuels, particularly with coal. Nowadays, another means of its exploitation, mainly in thermo-chemical conversion technologies such as pyrolysis, gasification, anaerobic digestion have minor significance in bio-energy production [2].

Biomass is highly volatile fuel. The burning velocity of pulverized is considerably higher than that of coals [1]. It can be burned in the flame in the same way as oil or gas fuels [1, 3].

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.

Taking the above into account, biomass co-combustion process is difficult to maintain at the desired operating point. Ensuring proper operational conditions can be obtained when a combustion diagnostic system is applied.

Flame, being the main reaction zone of a combustion process provides in fact undelayed information of combustion process state. 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 non-intrusive characterization and assessment of combustion process, that can be held in real-time [4]. Analysis of flame images allows to determine various parameters of flame such as geometric (e.g. size, position).

Laboratory stand

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 (10% by mass) with coal after passing through the feeder.

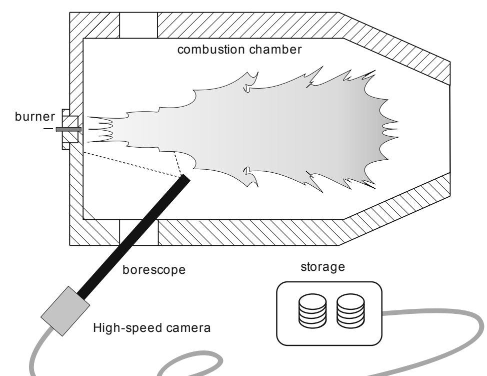


Fig.1. Combustion test setup

The combustion chamber has two lateral inspection openings on its both sides, that provide optical access. A boresope with high-speed camera attached sensor was placed near burner’s nozzle, as shown in fig. 1. The camera has color CMOS area scan sensor capable to catch 500 frames per second (fps). The borescope’s direction of view was 90 degrees to its axis. Flame images were transferred from the interior of the combustion chamber through a 0.7m borescope and were captured at a speed of 150 fps at full resolution (1280×1024 pixels), transferred and then stored in a high performance storage system. The optical parts were cooled with water jacket. Additionally, purging air was used to avoid dustiness.

Laboratory combustion tests

Several combustion tests were performed during which blend of pulverized coal and straw was burned for different settings of the combustion facility. Fuel and air flow rates were set independently and kept at the same level. The scale measured amount of fuel that was stored in the bunker. As the feeder had delivered the fuel blend to the burner, scale readings had tended to decrease. Fuel flow was calculated as a quotient of difference between two successive readings of scale and length of time interval between them. The plot showing the settings of air an fuel flows is presented in figure 2.

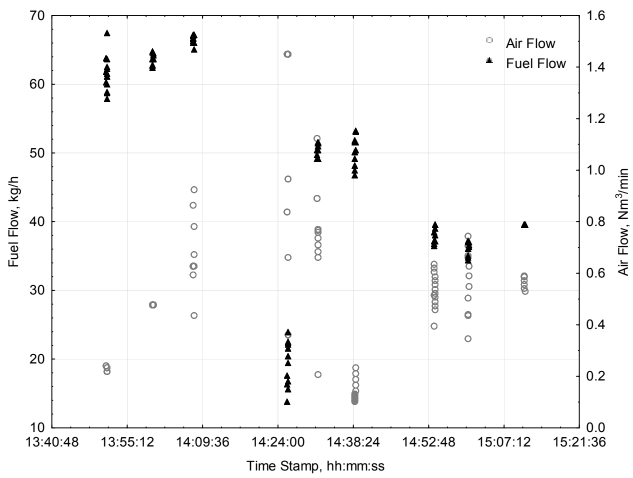
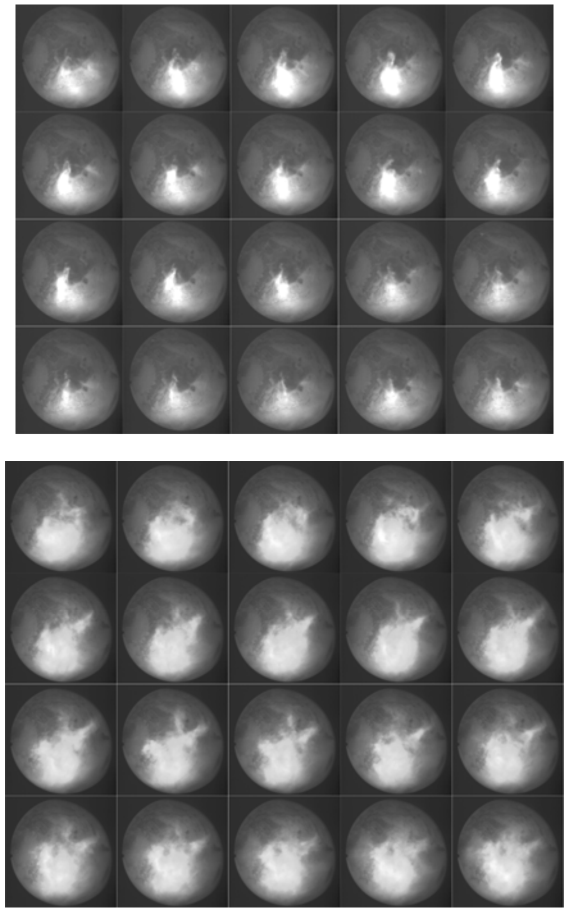


Fig.2. Air and fuel flows during the combustion test.

The experiment took about four hours while image sequence recordings lasted for about 30 seconds during which combustion state was in stationary condition. It was due to vast amount of storage memory that would be needed during the whole combustion test that usually lasted for 3 up to 5 hours. The fuel and air flows, as well as the other parameters of the stand were recorded in one second intervals whereas a number of images captured is equal to 150.

Nine combustion states were set. During the first three, fuel flow was comparatively high, reaching 58 ÷ 68 kg/h whereas fuel flow were adjusted at three levels. The fourth recording was made at the lowest fuel flows (around 20kg/h) with higher, but not steady air flow. The next two combustion process states fuel flow rate was around 50kg/h with higher and lower air flows, respectively. The last three states were conducted at fuel flows rate slightly lower than 40 kg/h.

Color images (24bit RGB) of flame were captured for mentioned above variants and stored in an uncompressed form. Example two sequences for two different combustion states were presented in figure 3. As it can be noticed, flame shape is different for different settings of air as well as pulverized fuel flow rate.



a)

b)

Fig.3. An example frame sequences captured for two different settings of fuel and air flows: a) captured at 13:51:13, b) at 14:07:45

Analysis of data obtained

In the case of coal-biomass flames, the dominant mechanism of radiation generation, apart from radiation emitted by hot gases and chemiluminescence, is thermal radiation emitted by solid particles [7]. Assuming the luminous particles are grey body spectral distribution of the radiation emitted by flame can be determined according to Planck’s law:

$$u(\lambda,T)=\varepsilon(\lambda)\frac{2hc^2}{\lambda^5}\cdot\left(e^{\frac{hc}{\lambda kT}}-1\right)^{-1}, \tag{1}$$

where: $u(\lambda,T)$ – irradiance for a given wavelength λ and temperature T, $\varepsilon(\lambda)$ - emissivity, h – the Planck constant, c – the speed of light, k – the Boltzmann constant.

Temperature inside the combustion chamber was equal to about 1200°C. Spectral power distribution of blackbody at temperatures ranging from 1000°C to 1300°C is presented in figure 4.

Flame images were captured by a color camera. As it can be seen in figure 4, for the case of flame images being analyzed radiation, intensity corresponding to blue and green color components is a few orders of magnitude lower than that of red. This is because only red component was applied in determination of flame area rather than luminance that is affected by noisy green and blue components. Thus, images containing only red component was further processed as grayscale objects.

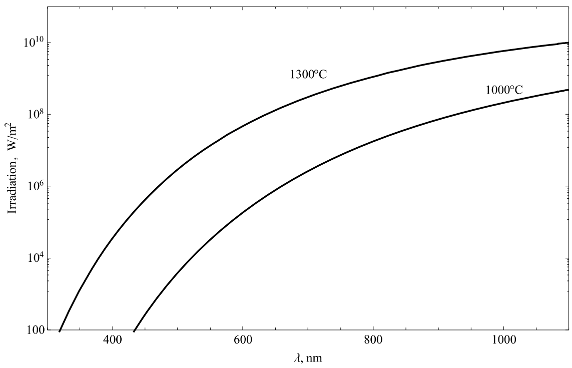


Fig.4. Spectral power distribution of blackbody for temperatures within the range 1000°C -1300°C

Several flame area parameters has been examined as variables that are dependent on combustion process input parameters as fuel and air flow. Magnitude of flame area and its brightness points to amount of fuel and air that are delivered in a unit of time. Flame area placement inside combustion chamber are another parameter examined by many for combustion process characterization [4,5,6]. For the combustion process, especially in presence of turbulent flame is highly nonstationary, mean values and standard deviations of the flame parameters were examined within time span equals to 1s. It has corresponded to 150 frames of video signal being analyzed.

In order to minimize the influence if background, the flame region was determined by Otsu's global thresholding method [7] (figure 5c), that can be applied when image histogram is bimodal, as it does in the case being discussed, as shown in figure 5b. Greyscale flame region was obtained as subtraction of a given image frame and the negative of flame region obtained by Otsu's method and is presented in figure 5d.

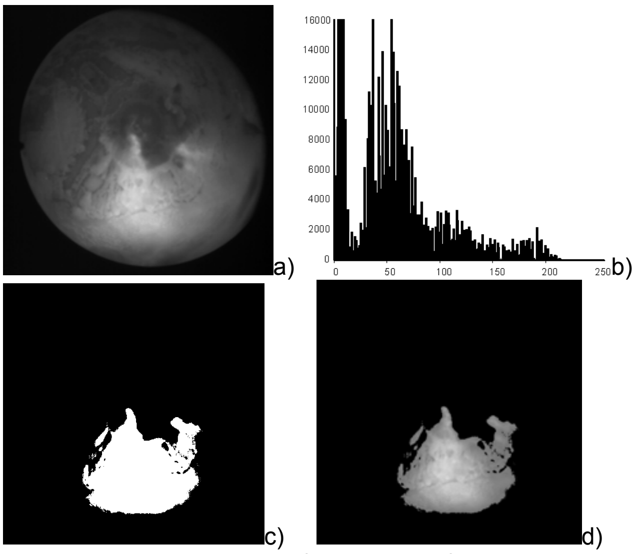


Fig.5. a) The R component of an example frame, b) histogram obtained, c) flame region obtained with Otsu's global thersholding method, d) greyscale flame area

Its area can be calculated according to the following formula:

(2) $$Area\ grey = \sum_{x,y \in A} g(x,y),$$

where A is greyscale flame region and $g(x,y)$ – luminosity of a grey pixel at coordinates x, y.

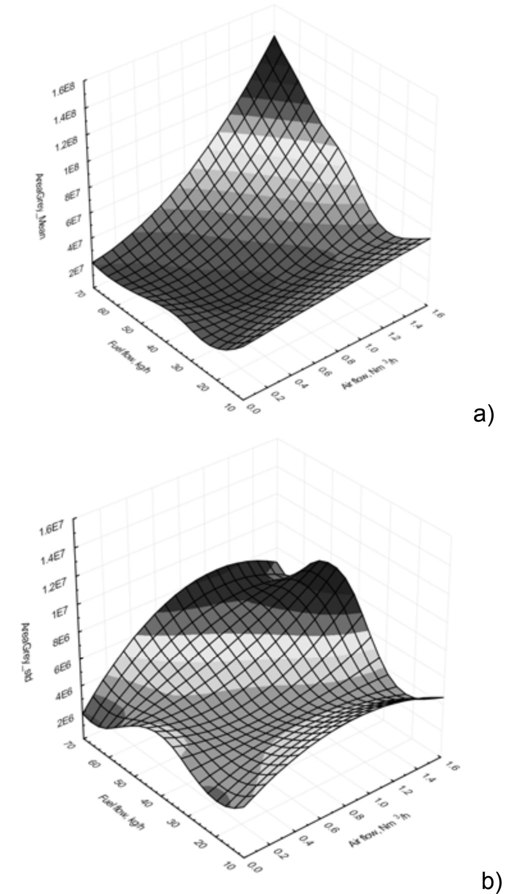


Fig.6. Changes of mean value (a) and standard deviation (b) of greyscale area region in dependence of fuel and air flow rates

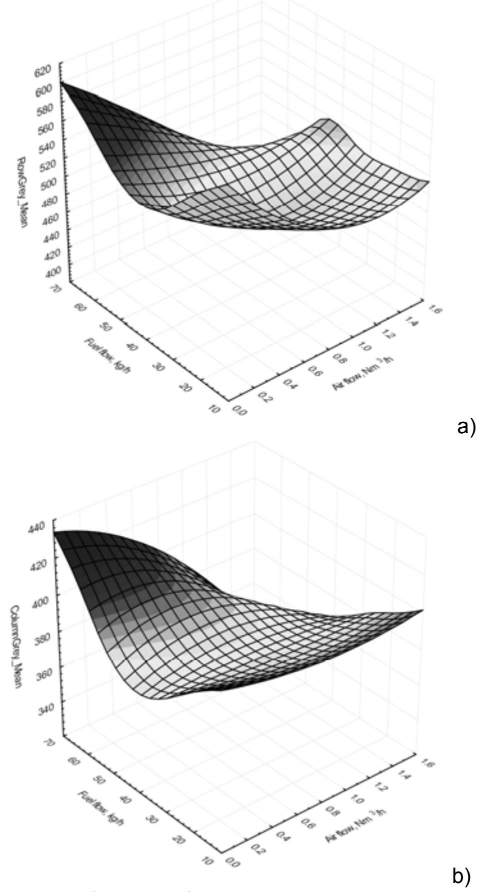


Fig.7. Changes of center of gravity coordinates in dependence of fuel and air flow rates

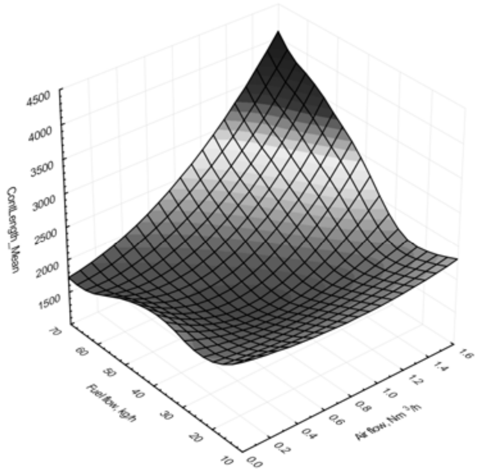


Fig. 8 Changes of averaged flame area contour length

Coordinates of greyscale flame region center of gravity is defined by the first two normalized moments of $g(x,y)$, i.e., by ($m_{1,0}$; $m_{0,1}$), where:

$$m_{p,q} = \frac{1}{Area\ grey} \sum_{x,y \in A} x^p y^q g(x,y). \tag{3}$$

Length of flame contour is 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 on the diagonal is rated $\sqrt{2}$.
The resulting flame parameters, that were determined during cofiring test are presented in figures 6-8.

Conclusions

Generally, The more fuel an air is delivered to the burner, flame area rises, as seen in figure 6a), although in case of fuel flow it is hard to describe it as monotonic. Similar dependence is reported for standard deviation of flame area. The coordinates of flame area centre of gravity (figure 7) points to flame shifting in the plane being observed. The results indicates that flame is slightly shifted for lower ait flow rates and higher fuel flows. Dependence of averaged values of flame area contour length on the air and fuel flows is similar to that obtained for the averaged area, as shown in figure 8a).

The experiment was made for only one composition of fuel mixture. It was assumed that the fuel is homogeneous. The results obtained can be helpful in developing automatic assessment of combustion process state, that can be held with vision methods in real time. However, the results strongly depends on the way of camera mounting as well as geometry of combustion chamber. Thus it is hard to generalize the results obtained to full-scale facilities. It would require preliminary tests in a target facility.

Authors: *dr hab. inż. Andrzej Kotyra, Lublin University of Technology, ul. Nadbystrzycka 38a, 20-618 Lublin, E-mail: a.kotyra@pollub.pl; prof. dr hab. inż. Waldemar Wójcik, Lublin University of Technology, ul. Nadbystrzycka 38a, 20-618 Lublin, E-mail: waldemar.wojcik@pollub.pl; dr inż. Konrad Gromaszek, Lublin University of Technology, ul. Nadbystrzycka 38a, 20-618 Lublin, E-mail: k.gromaszek@pollub.pl; Gulmira Bazil,* Kazakh *National Technical University after K. I. Satpaev, Satpaeva 22, Almaty, Kazakhstan, E-mail: bazil_g@bk.ru;*

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