Development and optimization of a control algorithm for an industrial combustion plant via flame image analysis

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Manuscript published as chapter of:

Book of Proceedings of STEPsCON 2018

Development and optimization of a control algorithm for an industrial combustion plant via flame image analysis

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Abstract

Modern industrial biomass combustion plants are regulated by the power and/or combustion control. In this process, the implemented sensors collect the relevant measured data. The aim is to achieve ideal combustion with optimum efficiency and to minimize gas emissions. For this purpose, a group within the research project Metabolon developed new regulatory procedures in order to record the combustion process of a biomass combustion plant using a webcam. The recordings were evaluated automatically and were used for a better monitoring of the process. In addition, the webcam-based method aims, among other things, to provide private homes with a cost-effective variant as an alternative to industrial system solutions.

1. Introduction

The recorded flame images provide information on the quality of combustion by fractionizing the flame into its components such as the flame area and color values. From these parameters, the efficiency, excess air ratio and CO concentration can be determined. Table 1 illustrates the relationship between the flame images in combustion with different levels of excess air and the resulting findings.

Every combustion of biomass requires the largest possible flame surface because a large flame surface usually leads to low excess air. On the other hand, if the excess air ratio is too large, the flame area decreases because the cold air cool down the flame. Furthermore, the large flame surface indicates that there is a high level of efficiency and low pollution levels [1].

Combustion with low excess air There is a large area of flame but with a reddish flame color and many dark areas in the flame. For this reason, it comes to a strong soot formation and a high CO concentration with a medium to high efficiency [1].	
Combustion with to high excess air The flame surface is very small, because the existing air is cooling down the flame. As a result, the efficiency drops below 50%. The CO emission is very high and there is virtually no soot formation [1].	
Combustion with a very good air ratio There is a medium to high efficiency which occurs in a semi-transparent golden yellow flame. Both soot formations and pollutant emissions are low [1].	
Optimal combustion The flame is beautifully bright and has a golden yellow color. Under this condition, there is a medium to high soot formation. However, the CO concentration has a low to medium value at a high efficiency [1].	

Table 1: Representation of the flame images as well as consequences under the influence of different high excess air [1]

2. Measurement

The combustion process is recorded with a camera system and converted into a binary image. The creation of the binary images is done according to the thresholding method of Otsu. Based on this method, a defined threshold indicates the range of the pixel brightness in the image from black (binary value 0) to white (binary value 1). The white pixels represent the flame, whereas the black pixels represent the background of the image. The ratio of the white colored area to the total area indicates the size of the flame. For further procedures, only the flame binary image is crucial. For this reason, the edited binary image is overlaid upon the original image so that the background disappears and only a portion of the flame remains. In order to obtain color information of the flame from the white flame section, the image is converted into a CIELAB color space and then processed using a method of vector quantization based on k-means clustering. With this algorithm, three different clusters are created which contain the three flame colors (red, yellow and white). Based on these color components, the corresponding temperature of the combustion can be identified [2].

Furthermore, a measurement of the flame under both optimal and noisy combustion conditions must be carried out in order to determine the basic values for the respective states. The combustion is either in the optimal state or there is a disturbance in the form of too much air or lack of air. The noisy combustion state increases soot formation as well as pollutant emissions. By testing different measurement times, it has been proven that one measurement every 20 seconds is best suited. However, in order to counteract the strong fluctuations of the flame and thus of the color values, an average value of the measurements must be determined every minute (Diagrams 1 und 2) [3].

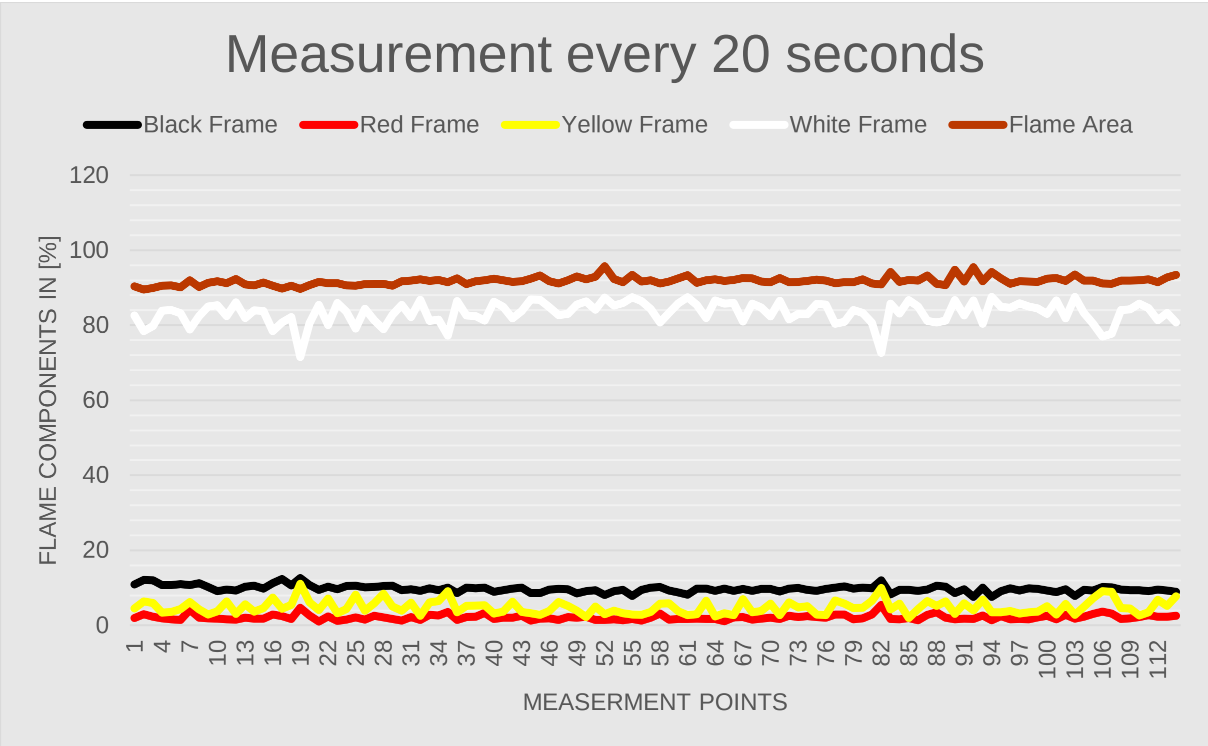


Diagram 1: Recording of the measuring points every 20 seconds

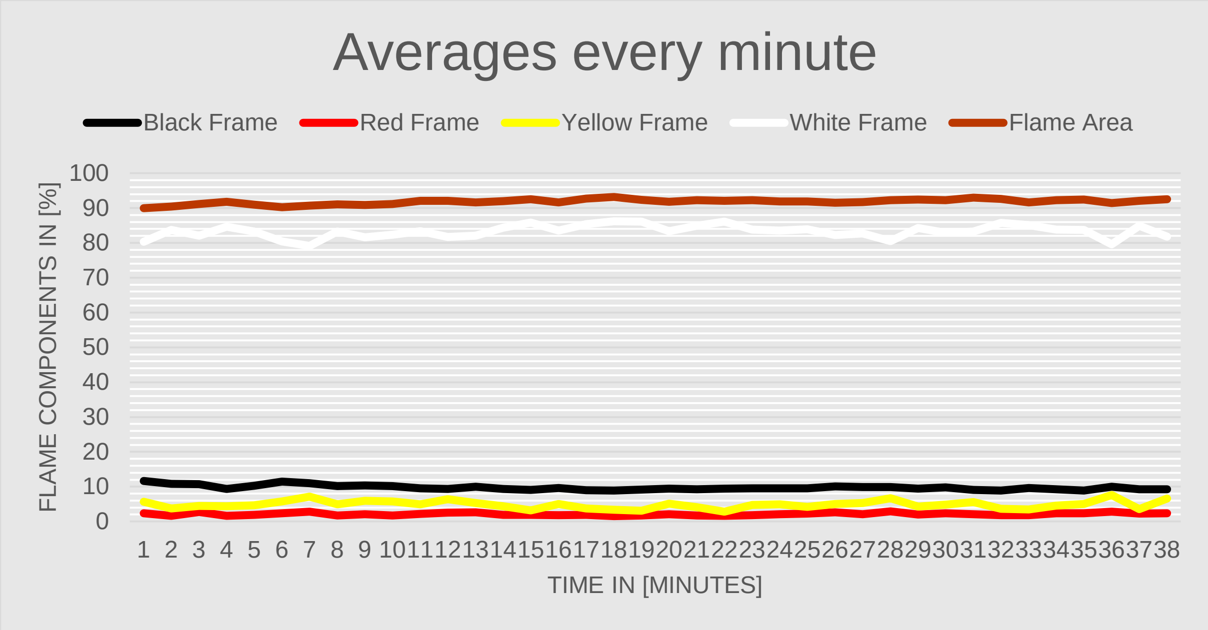


Diagram 2: Formation of the average value

Because of the different compositions and thus different energy densities of the fuel (wood chips), the secondary air supply varies. In order to calculate an optimal secondary air supply, the control is based on the successive approximation in which the optimal secondary air supply is calculated by a stepwise approximation [3].

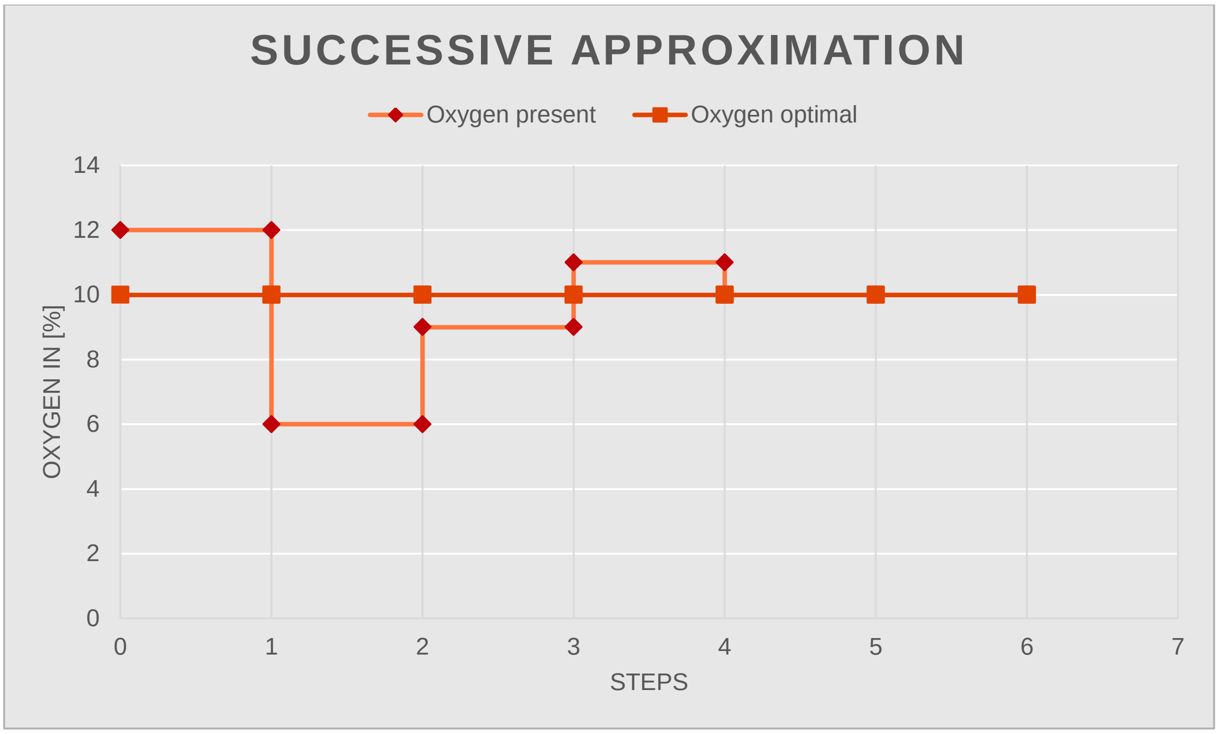


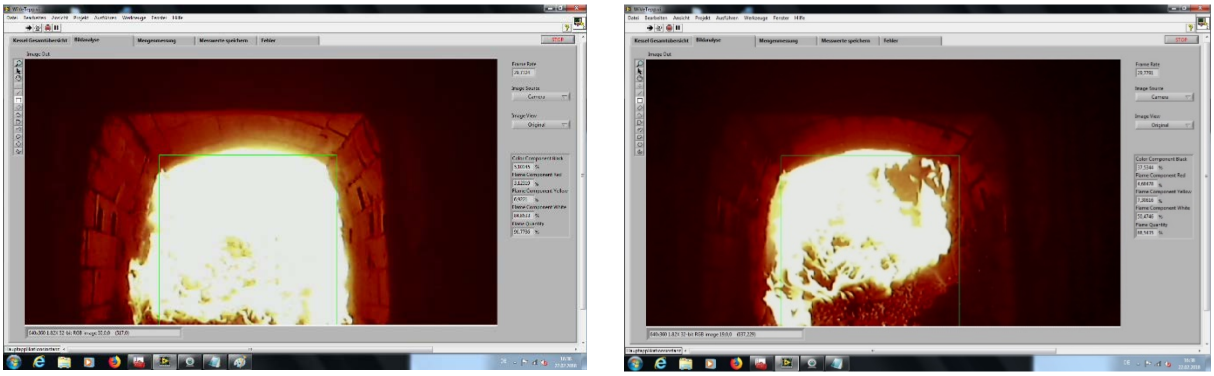
Diagram 3: Successive Approximation

The graphic shows an example of the procedure of a successive approximation when changing to a new type of fuel. The plant was previously operated with a fuel that was optimally burned at a residual oxygen content of 12%. By switching to a new fuel, the residual oxygen for optimal combustion was also changed. How high this is now must be determined. For a better illustration, the orange curve in the graph represents the new optimum residual oxygen content. Under this course there is a lack of air, which is also recognized by the webcam. Thus, the controller samples the optimum residual oxygen by controlling the secondary air supply in such a way that the residual oxygen content in the exhaust gas is halved with each step.

3. Results & Discussion

The project is not yet completed. For this reason, only the intermediate results already acquired are presented and discussed here.

The measurements were carried out under optimal combustion, settings by the manufacturer, and under the simulation of a lack of air. The following flame pictures including measurements were taken.



Picture 1: On the left is the flame picture with an optimal combustion. On the right is an image capture with a simulation of a lack of air

The lack of air was simulated by gradually closing the inlet grilles for both the primary and secondary air supplies of the firing system completely, although the secondary air supply is of greater interest to us than the primary one. This is due to the fact that the primary air supply is coupled to the combustion chamber temperature and thus cannot be influenced by the PLC control. Nonetheless, the following measurement results of the flame and the exhaust gas were recorded for both cases.

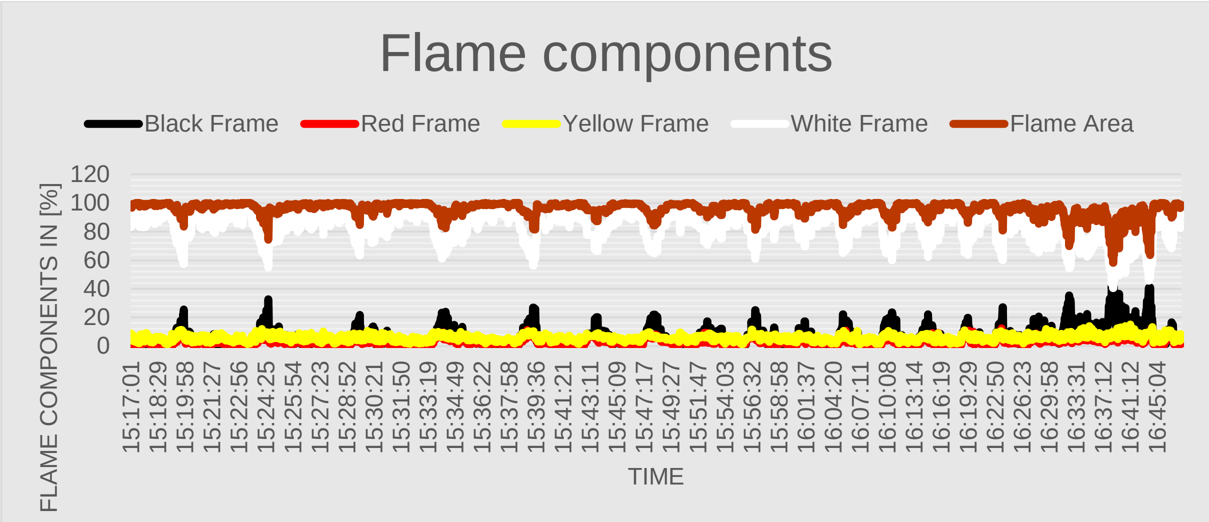


Diagram 4: Recorded Flame components

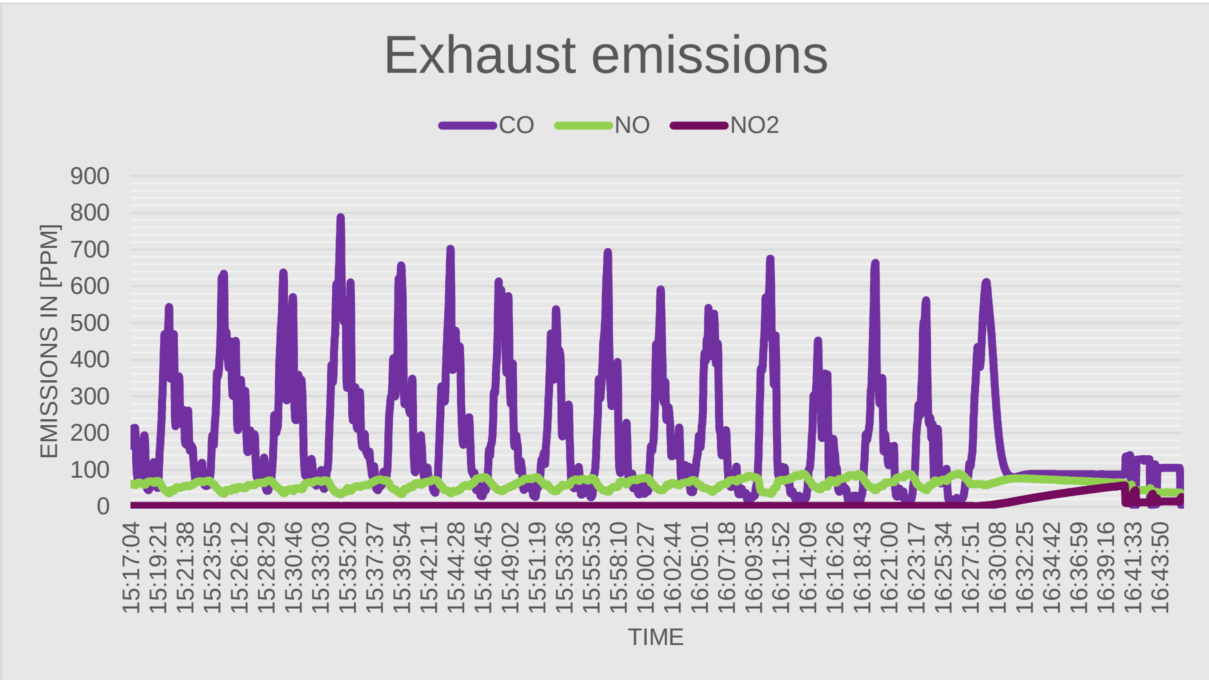


Diagram 5: Recorded exhaust emissions. CO is carbon monoxide, NO is nitrogen oxide and NO2 is nitrogen dioxide

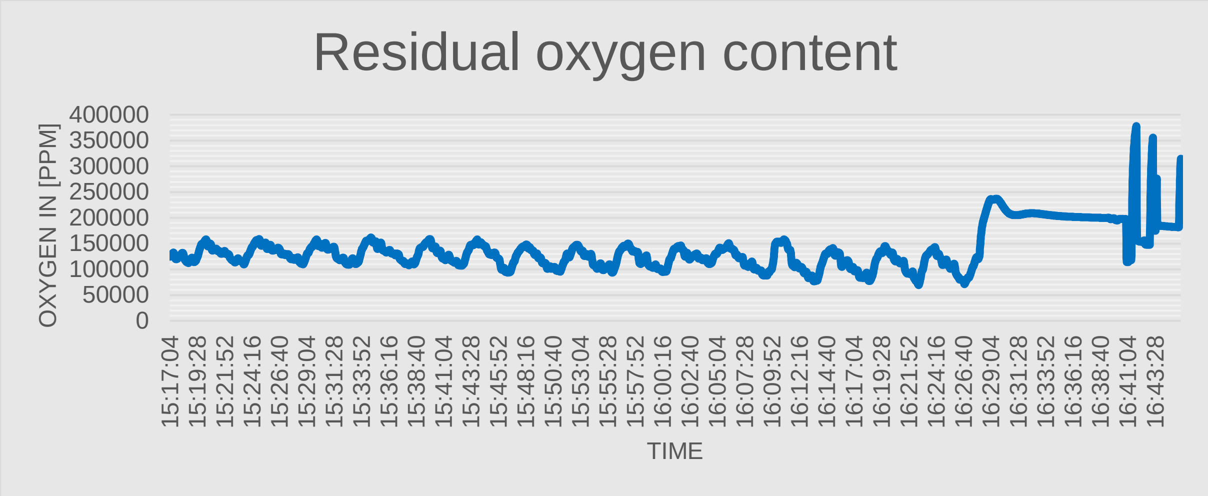


Diagram 6: Recorded residual oxygen content in the exhaust gas

The measured values were recorded every second in order to be able to better detect the reaction to simulated disturbances in a combustion process and to be able to determine the basic values more precisely later. Furthermore, measurements were recorded in the firebox of the furnace. As can be seen from the diagrams 4-6, recording of the measured values started at 15:17:01. The exhaust gas required about 3 seconds to travel from the combustion chamber to the measuring point at which the emissions in the exhaust gas were measured. For this reason, the exhaust emission graphs are offset by 3 seconds compared to the flame component measurement. Starting at 15:28, the intake grille for the secondary air supply was gradually closed to simulate a lack of air in the combustion process. However, it turned out that e.g. the flame surface together with the white part of the flame decreased for a short time and the black part increased, but later on the system tried to counteract the disturbance and the values cancel each other out, so that fluctuations took place. The occurring fluctuations increased from about 15:39 on. This can be seen very clearly in the short intervals.

Closing the intake grilles only increased the fluctuations in the measured values. However, the flame area did not decrease and the emissions did not increase permanently. Actually, it was expected that the flame area would shrink and the color values would also decrease. On the other hand, emissions would have to increase and remain high at all times. Therefore, the intake grilles for the primary air supply were gradually sealed airtight from 16:10 until they were closed at 16:18 to 98%. At 16:30, the influence of air deficiency on the flame could be observed for the first time (see Figure 1). It can also be clearly seen from diagram 4 that e.g. the flame surface and the white content break sharply.

Conclusions

Due to the fact that the air deficiency could only be simulated conditionally, the threshold value for the controller could not be calculated. Consequently, a new process has to be developed to gradually simulate the lack of air. Furthermore, in the new simulation method, additional parameters such as e.g. the timing of the fuel supply or the negative pressure in the furnace are taken into account.

Currently, a new model is being developed to detect the disturbances even better and more accurately. This model focuses on the evaluation of the combustion according to the load factor, color of the flame, the timing of the fuel and the secondary oxygen supply. The evaluation as well as the recording of the measured values is based on the design of experiments (DOE).

Unfortunately, the control could not be tested yet because the PLC control does not allow the control parameters to be taken over Modbus. At the moment, the control parameters can only be transferred manually via the panel. Therefore, a new PLC control is needed to avoid this problem. Alternatively, it should also be checked whether the developed controller can be connected directly to the frequency inverter in order to be able to directly control the secondary air supply in this way.

Acknowledgements

The authors would like to thank the “Bergischer Abfallwirtschaftsverband” (BAV) for the excellent cooperation. A share of the funding for this study is made by the European Commission and the European Regional Development Fund (ERDF) under the slogan “Investing in our future”. The authors have declared no conflict of interest.

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