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Optical methods and artificial intelligence in diagnostics of industrial pulverized coal burner

***Abstract**. In order to meet very stringent emission standards the modern combustion technologies require advanced diagnostic methods such as optical methods. They provide large amounts of information, but their interpretation requires the use of complex data processing techniques. The article describes a method developed by the authors and the results of the research made using 1:10 scale model. (**Metody optyczne i sztuczna inteligencja w diagnostyce przemysłowego palnika pyłowego**)*

***Streszczenie.** Współczesne technologie spalania, aby spełnić bardzo ostre normy emisji zanieczyszczeń wymagają zaawansowanych metod diagnostyki np. z użyciem metod optycznych. Dostarczają one dużej ilości informacji lecz ich interpretacja wymaga zastosowania złożonych technik obróbki danych. W artykule opisana jest metoda opracowywana przez autorów i wyniki badań na modelu w skali 1:10.*

Keywords: diagnostics, combustion, fuzzy modelling, NOx emission.
Słowa kluczowe: diagnostyka, spalanie, modelowanie rozmyte, emisja NOx.

Introduction

The premise for the exploration of new methods of diagnostics of the combustion process are the difficulties encountered during the implementation of low emission combustion technology. The combustion process is then run very close to the limit of flammability, which can cause a sharp increase in CO emission, unstable combustion and finally the flame blowout. Measurement of the majority of combustion parameters such as CO, NOx, and oxygen in the exhaust gas can be easily made by using gas analyzers, but the measurement results obtained in this way are significantly delayed and averaged over all the burners in the boiler.

The analysis of the problem let us conclude that there is a lack of method that allows measurement of output parameters of an individual burner like for example NOx or CO emission level. It is therefore necessary to use indirect methods, which could primarily include acoustic, and optical methods [1, 2]. These methods are noninvasive and can be obtained virtually not delayed and additionally spatially selective information about the combustion process. The authors put the thesis that it is also possible to obtain quantitative information on the basis of optical signals originated by a flame. In the article it is demonstrated on the example of nitrogen oxides. Due to the highly nonlinear nature of dependency and lack of an analytical model fuzzy neural networks were used for modelling of emission from turbulent flame. The paper describes the use of methods with a relatively small computational complexity. The work of the research team also includes the use of more complex methods such as Fourier, wavelet and curvelet transforms [3, 4].

Research methodology

Combustion of pulverized coal was examined through optical methods, that were based on analysis of radiation emitted by the flame. The analysis also takes into account spatial features of such radiation source. Estimation of NOx content within the flame of an individual burner based on emission spectrum analysis is possible, yet it can be hardly done in harsh, industrial conditions, especially with presence of high temperature, vibrations and dustiness. It was decided therefore to apply a different approach.

Combustion of pulverized coal in the power burner takes place in a turbulent flow. In its each point local fluctuations of both fuel and gaseous reagents concentrations, as well as temperature occur. It leads to permanent local changes in combustion process intensity, which result in continuous changes in flame luminosity that can be observed as flame flicker. As combustion process affects the turbulent movement of its products and reagents it determines the way the flame flicker parameters such as e.g. mean luminosity and luminosity frequency spectrum. A number of combustion supervision and flame-fault protection systems and use information contained within flame flicker. The multichannel fibre-optic flame monitoring system developed at Lublin University of Technology is an example solution of that kind. Detailed description of the system is presented in [5]. It allows observation of selected areas of the flame and converting the optical signal into an electric one for further processing. The measuring probe is placed inside a combustion chamber, close to burner and is exposed to temperatures of the order of hundreds degrees centigrade. Its construction ensure a long-term operation inside the combustion chamber by the air that purges the probe end. A photograph of multichannel measuring probe is shown in fig. 1.

Fig.1. Multichannel fiber-optic measuring probe.

Experimental facility and experiments

Experiments were made on test rig located in the Institute of Power Engineering in Warsaw. It is a combustion chamber with a single pulverized coal swirl burner made in 1:10 scale in relation to a low-emission industrial burner. This object was chosen because of the ability to perform experiments with a single burner, and it's a good instrumentation. All measured and some calculated quantities – relevant to the combustion process operation – are visualized and recorded by the data acquisition system. Sampling period is 1s. The combustion chamber is equipped with a fibre optic probe allows observation of five different areas of the flame. Figure 2 shows a section of part of the chamber with marked areas of view as well as the view of fiber optic probe placement.

The experiment begins with bringing the chamber to the proper temperature first using the oil burner and then the pulverized coal burner. When the temperature in the chamber reaches a level sufficient for stable burning of pulverized coal, the oil burner is turned off. When the temperature stabilizes the series of measurements are performed. Each measurement corresponds to different combination of air flow, swirl angle, thermal charge and percentage of biomass co-fired. A single measurement lasts approximately 300 seconds.

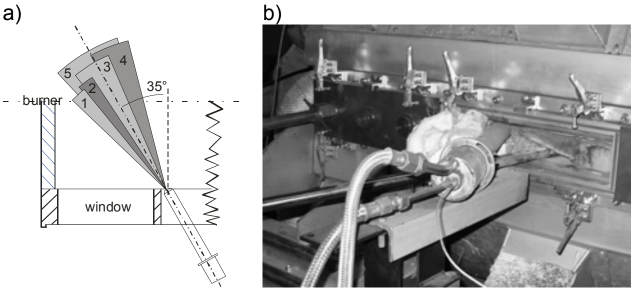

Fig.2. Fields of view of fibers (a) and view the installed probe (b).

During an individual measurement the amounts of fuel and air are kept constant. Such measurement method is to eliminate the impact of the transport delay of gas analyzers. It is assumed that during each measurement the conditions are stationary and the emission values stabilized. This is important because of the impact of negative pressure in the combustion chamber on delays and difficulties in obtaining the same vacuum value for all measurements. On the other hand, this strategy prevents the training of dynamic neural networks due to the data discontinuity.

Results of experiments

Voltage signals corresponding to the instantaneous brightness of the flame of the areas observed by the individual optical fibres were sampled at a rate 1KS/s and saved by a dedicated system. After completing the measurements the following parameters of these signals within one second were calculated: the average intensity value, intensity variance, number of mean value crossings and (changes of sign) of the signal derivative. Such choice of parameters was made on the basis of previous studies [6].

The dependence of these parameters on the conditions of combustion of pulverized coal is evident, but this information is not very useful from the standpoint of managing the process of combustion. Then the next step is such processing of these parameters to give information about the important parameter of the combustion process, such as the fuel / air ratio, the content a given compound in flue gases, etc. The nitrogen oxide emission was selected for further analysis.

In order to preliminarily assess the suitability of specific parameters for further study the linear regression analysis was performed in order to find correlations between the parameters of the optical signal from each fibre, and nitrogen oxide emission. Their figure for the cumulative measurements at different conditions of combustion are shown in Table 1.

Table 1. Chosen time series parameters correlation with NOx emission

fibre	mean	variance	mean crossing	derivative zero cross.
1	0,2473	0,0019	-0,1498	0,0413
2	0,3941	-0,0419	0,0124	0,0518
3	0,4363	-0,0141	-0,0222	0,2063
4	0,4806	0,0882	-0,1522	0,2051
5	0,4549	0,0667	-0,0270	0,1374

None of the considered signal parameters is correlated with NOx emissions strongly enough to be used alone to determine this quantity. Weak linear correlation with the apparent dependence may also indicate that this relationship is nonlinear. Magnitude of the optical signal intensity, despite a relatively strong correlation with NOx emissions, cannot be used alone for yet another reason. The average intensity may be dependent on the status of the optical path, for example dirt causes a drop in the signal. The possibility of such a factor leads to the conclusion to use signals not dependent on the DC component of intensity (number of mean value crossings and number of the signal derivative zero hits), but unfortunately, they are not too strongly correlated with the quantity under consideration. Due to the weak correlation for all four parameters of fibers 1 and 2, their usefulness seems to be questionable. So, it seems that the best possible set of data to model NOx emissions is the intensity and the number of zeros of the derivative from fibres 3, 4 and 5.

Neuro-fuzzy modelling

The combination of neural networks with fuzzy logic has many benefits, especially where traditional methods and solutions do not give good results or use them for specific tasks would be too time-consuming or costly. Neuro-fuzzy is one of concepts of the artificial intelligence that refers to combinations of artificial neural networks and fuzzy logic, Such hybrid intelligent system synergizes these two techniques by combining the connectionist structure of neural networks and the human-like reasoning style of fuzzy systems through the use of fuzzy sets and a linguistic model consisting of a set of IF-THEN fuzzy rules. The main strength of neuro-fuzzy systems is that they are universal approximators with the ability to solicit interpretable IF-THEN rules, yet it involves two contradictory requirements in fuzzy modeling: interpretability versus accuracy. The approach presented in the article focuses on the later one, implementing the Takagi-Sugeno-Kang (TSK) model.

Matlab fuzzy logic toolbox and its ANFIS (adaptive neuro-fuzzy inference system) tool was used to design neuro-fuzzy models. The tool allows constructing and training Sugeno models using methods typical for neural networks, e.g error backpropagation. For this purpose the fuzzy model is converted into equivalent neural network with structure of multilayer perceptron.Due to the strategy of measurements the data was grouped in distinct centers so the fuzzy rules were generated by subtractive clustering.

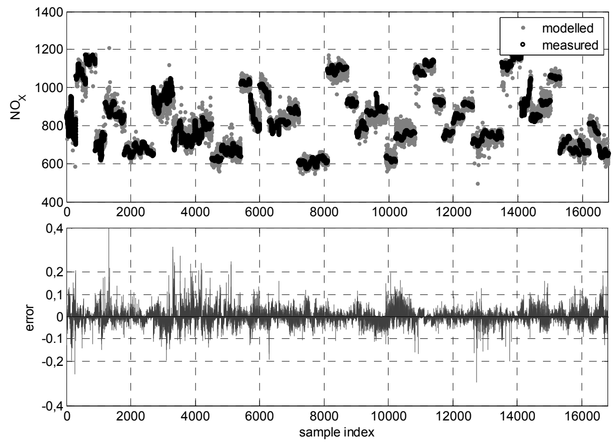

Fig.3. Sets of values measured and calculated on the basis of optical signals (above) and a set of corresponding modeling error.

Tests using all 20 parameters were performed as a reference. Figure 3 shows the sets of values measured and calculated on the basis of optical signals and a the set of corresponding modeling errors for a network with 56 membership functions. Only 1.26% out of the 17000 measurements the model error exceeded 10%. There are also gross errors above 20% virtually only in measurement series in which it was impossible to maintain the constant level of emissions during the entire series. Table 2 contains parameters of the model errors of nitrogen oxide emissions, using all 20 parameters for different number of membership functions.

Table 2. Error characteristics for NOx emissions model using all 20 parameters

error parameter	Number of membership functions			
	6	12	27	56
minimum	-0.3477	-0.4419	-0.4419	-0.2949
maximum	0.6298	0.4986	0.4986	0.4057
mean val.	0.0040	0.0028	0.0028	0.0012
std. dev.	0.0647	0.0538	0.0538	0.0355
err>10%*	6.51%	4.05%	2.22%	1.26%

* percentage of errors greater than 10%

Table 3. Error characteristics for NOx emissions model using the mean signal intensity and the number of signal derivative zeros.

error parameter	Number of membership functions			
	15	22	32	59
minimum	-0,5522	-0,3348	-0,5551	-0,3402
maximum	0,5032	0,3659	0,3567	0,3552
mean val.	0,0024	0,0016	0,0013	0,0012
std. dev.	0,0500	0,0407	0,0375	0,0342
err>10%*	3,76%	1,85%	1,5%	1,2%

* percentage of errors greater than 10%

Tests carried out using only the parameters that are independent of intensity proved too high model error, even for a large database of rules, more than 25% of the samples was burdened by an error above 10%. According to the linear regression analysis, new models were constructed using only the intensity and the number of zeros of the optical signal derivative. For 32 membership functions, the percentage of errors exceeding 10% was 1.5% and further increasing their number did not result in a significant decrease in error (Table 2).

In order to further reduce the number of inputs we have examined models that use the same signals from fewer fibers, but their error was significantly higher. So the impact of a high correlation of mean intensity with model output quantity is evident.

A peculiarity is the fact that in the case of liquid and gaseous fuels variance (or standard deviation) of the optical signal showed a high correlation with the size of the NOx emissions [7, 8], while in the case of pulverized coal, this parameter plays a marginal role.

Conclusions and remarks

The optical signal is the fastest one and provides selective way of getting information about the quality of combustion. It can be used for diagnostics of an individual burner. However its interpretation, poses many difficulties.

The results of the use of modern methods of obtaining information about the quality of combustion (e.g. about NOx emissions), described in the article appear to be promising. However, the accuracy and repeatability of measurements still requires further research.

The studies, described in the article, confirm that in order to obtain NOx emissions from pulverized coal burner the estimate calculated on the basis of immediate optical signals can be used instead of the delayed signals from the gas analyzers. The use of neuro-fuzzy models allows to determine emissions of nitrogen oxides with satisfactory accuracy and time, what allows application in control systems.

Preliminary research proved the influence of variations in fuel composition on the analyzed parameters. Its quantitative determination requires further studies.

The use of genetic algorithms [9, 10] should assure better exploitation of information contained in the optical signal. Preliminary results of their application indicate that they may improve the control of combustion process.

The experiment technique requires modification. The assumption of the measurement strategy was the constancy of process input and output parameters during each individual measurement. Analysis of the measurements shows that the models have the greatest error in cases where they failed to keep the variability of the emissions on a small level.

REFERENCES

[1] Dowling A.P., Stow S.R., "Acoustic analysis of gas turbine combustors", *Journal of Propulsion and Power*, vol. 19, no. 5: 751–763 (2003)

[2] Docquier N, Candel S., "Combustion control and sensors: a review", *Prog Energy Comb Sci*, 28: 107–50 (2002)

[3] Wójcik W., Kotyra A., Ławicki T., Pilek B., "Application of curvelet transform in accessing of pulverized coal combustion", *Przegląd Elektrotechniczny (Electrical Review)* Vol. 2010, No 7: 247-249, (2010)

[4] Wójcik W., Kotyra A., Komada P., Przyłucki S., Smolarz A., Golec T., "The methods of choosing the proper wavelet for analyzing the signals of the flame monitoring system", *Proceedings of SPIE, Optoelectronic and Electronic Sensor V*, Volume 5124, 2003, pp.226-231

[5] Wójcik W., Surtel W., Smolarz A., Kotyra A., Komada P., "Optical fiber system for combustion quality analysis in power boilers", Optoelectronic Information Technologies, Proceedings of SPIE, vol.4425, pp.517-522, 2001

[6] Smolarz A., Wójcik W., Kotyra A., Wojciechowski C., Komada P., "Fibre optic monitoring system", *Proceedings of SPIE on Lightguides and their applications*, vol. 4239, pp.129-132

[7] Smolarz A., Wójcik W., Ballester J., Hernandez R., Sanz A., Golec T., "Fuzzy controller for a lean premixed burner", *Przegląd Elektrotechniczny (Electrical Review),* Vol. 2010, No7: 287-289 (2010)

[8] Sanz A., Ballester J., Hernandez R., Cerecedo L.M., "Advanced monitoring of industrial burners based on fluctuating flame signals", *Fuel,* 87: 1063–1075 (2008)

[9] Wójcik W., Kalita M., Smolarz A., "The influence of evolutionary niche occurrnce on genetic controller operation in the power boiler", *Przegląd Elektrotechniczny (Electrical Review)* Vol.2008,No 3: 222-224 (2008)

[10] Wójcik W., Kalita M., Smolarz A., "The influence of selection type choice on genetic controller operation in the power boiler", *Przegląd Elektrotechniczny(Electrical Review)* Vol.2008, No 3: 225-227, (2008)

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