ADVANCED DIAGNOSTCIS OF INDUSTRIAL PULVERIZED COAL BURNER USING OPTICAL METHODS

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Abstract
Controlling the combustion process is a very complex issue. The difficulty of operation of such process consists in the mutual interference effects of chemical, physical (mainly energy and mechanical) on one hand and risks existing if its course becomes unpredictable. In addition, there are restrictions on the control due to the unavailability of certain process signals (input or output) and incomplete knowledge about them. Current availability of high-speed measuring and computing devices allows to extract the hidden relationships between the elements of such complex process and the use them in control. The paper presents the technologies being developed in the Department of Electronics Lublin University of Technology. They use optical diagnostic methods and artificial intelligence methods.
Research is aimed to develop a system allowing a parametric evaluation of the quality of pulverized coal burner operation. It is based on an analysis of local variability of the brightness of the flame. Due to the highly nonlinear nature of dependency and lack of an analytical model, fuzzy-neural methods were used to estimate the selected parameter.
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.

Introduction
Burning of fossil fuels is the main source of atmospheric pollution. Unfortunately it is impossible now and in the nearest future to avoid burning them for they are the main carrier of primary energy. Power industry and coal based especially has its important share in air pollution. Until the end of seventies the increase of power efficiency, durability and reliability was the main goal in design of burners and boilers. Protection of natural environment requirements, considering mainly nitrogen oxides' emission, caused radical change in their design. In order to decrease an amount of toxic substances originated in a combustion process the so-called low emissive combustion technology has been introduced. It generally consists in gradual supply of air, in order to create reduction zones in a flame, what reduces emission of gaseous pollutants. It basically applies to nitrogen oxides, denoted generally as NOx. The main advantage of such modifications is the reduction of NOx at relatively low investment cost. The low-emissive burner should not only assure limitation of NOx emission below an allowed lever but also has to maintain its other functional parameters such as stability within a range between 50% and 100% of the boiler nominal output. It should also ensure low carbon dioxide emission as well as contents of unburned particles in ashes below 5%.
Unfortunately, reduction of NOX emission by modification of combustion process has some negative side effects. The most important are: increased carbon oxide emission, incomplete combustion, increased level of unburned coal particles in the ashes, corrosion of evaporator, increased slagging and decreased heat transfer efficiency. These negative effects of

application of low-emissive technology of combustion are limiting the possible to achieve emission reduction. In order to avoid them the low-emissive burners have to be equipped with individual monitoring and diagnostic systems.
In order to minimise the consequences of the mentioned side effects it is necessary to obtain information about the course of combustion process as well as its adequate control. Both tasks are relatively difficult because of high complexity of phenomena proceeding during combustion. Commonly used control systems employ process variables such as: flow of the air-pulverised coal mixture from each mill, air fans load, unit power or emission of gasses (CO, O_2, NOx). There are also successful attempts to replace a classic controller with a neural network one [1, 2]. In spite of big complexity, all these systems have however one basic disadvantage: the control is based on averaged and heavily delayed measurements. There are tens of burners in a single power boiler and gas analysis is usually made using gas analysers with probes placed after air heaters (in the best case – frequently the gas analysis is bade in chimney, collectively for several power units). The delay is nonstationary and can reach even several minutes so the control often results ineffective. Even the most advanced of recently available control systems is not able to control an individual burner, while an individual air excess ratio rules an amount of NOx generated [3].
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 [4, 5, 6], and optical methods. 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 modeling of emission from turbulent flame.

Research methodology

Combustion of pulverized coal was examined through optical methods, that were based on analysis of radiation emitted by the flame. An analysis should take into account spatial features of such a radiation source, as well as mechanisms responsible for radiation generation and both scattering and absorption phenomena. For pulverized coal flame, the emitted radiation is composed of the following components:

- radiation that is emitted by hot particles, such as coal, coke, ash, soot,
- radiation that origins from chemiluminescence of radicals, mainly OH*, CH*, C_2*, HCN*, NH*, NH_2*,
- radiation emitted by hot gases as a result of thermal excitation.

Solid particles can be treated as a gray body. Thus, the intensity of radiation can be obtained by the Planck law:

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

where:

$u(\lambda,T)$ – radiation flux for an area unit (irradiation) for an unit solid angle ($W\cdot sr^{-1}\cdot m^{-2}$) for a given wavelength λ at temperature T,
$\varepsilon(\lambda)$ – the gray body emissivity for a given wavelength,
h – the Planck constant,
$c = 3\cdot10^8\ m\cdot s^{-1}$,
k – the Boltzmann constant.

Emissivity of a given body depends on many factors, among others, the most important are: temperature, wavelength and properties of the body surface. In case of coal particles that are burned together in a stream, emissivity can be determined experimentally. The resulting emission spectra are continuous and strong especially within the IR range. Assuming $\varepsilon(\lambda) = 1$, the maximum emissivity obtained for temperatures ranging from 1000K to 1800K corresponds to wavelengths from 2850nm to 1605nm respectively.

Radiation of chemiluminescence spectra consists of a few emission lines, that are grouped in bands distinctive for given radicals In case of pulverized coal flames, OH*, CH*, C_2*, CO_2* are the most important [7]. Their chemoluminescence spectra occurs mainly within the UV-VIS range. The nitride radicals NO*, HNO* and CN* are also present in the flames discussed.

Radicals' occurrence is narrowed mainly to the reaction zone for the molecules quickly tend to equilibrium. Radicals, such as OH*, CH*, CN* as well as the other combustion reaction products are created within flame front [8]. Emission spectra of OH* are well correlated with fuel-air ratio and can be used potentially as NOx indicators [9, 10].
Emission spectra of a pulverized coal flames are dominated by continuous spectrum of solid particles with emission lines of gaseous components, mainly gaseous products of coal pyrolysis and combustion gases – water vapour, NO, SO_2, CO and hydrocarbons. It should be underlined, that the dominant gas emission spectra components originate from water vapour and CO_2 [11].

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. What is more, 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 fiber-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 [14].

The mentioned system is designed for operations in harsh conditions. It provides signals corresponded to radiation that is generated within spatially limited flame zones. Generally, the systems consist of the following elements

- measuring probe,
- optical fiber bundle,
- photodetectors,
- signals processing unit.

A schematic diagram of a typical flame monitoring system is presented in fig. 1.

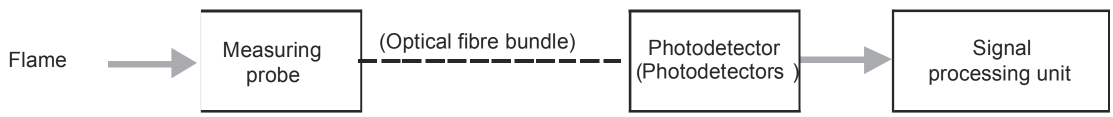


Figure 1. Main parts a typical flame monitoring system.

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.

Solid angles from which the radiation is delivered to the photodetectors is determined by the place of mounting the measuring probe and numerical aperture of optical fibers applied. Initially, probe's orientation is adjusted so as to provide the highest possible signal amplitude levels. A photograph of multichannel measuring probe is shown in fig. 2.

Figure 2. Multichannel fiber-optic measuring probe.

Optical fiber bundle enables to isolate signal processing unit from high temperatures conditions. Moreover, it makes mounting of the whole system more flexible. For the length of the fibers applied is of the order of a few meters, the attenuation of the optical signal within a spectral range of radiation emitted by a coal flame can be neglected. To maximize the radiation power acquired by measuring probe a thick-core PCS fibers was used or HCS fibers for their maximum temperature up to 350°C.

The photodetectors are placed beyond the measuring. For the detection of carbon flame radiation, photodetectors designed for visible or near-infrared range are suitable. Materials such as Si, Ge, InGaAs or so called the modified silicon are commonly used. The last one has better performance in the UV range, so it may be applied also for mazout flame detection. The spectral characteristic of the photodetector applied is presented in fig. 3. To minimize an influence of outer radio noise in industrial conditions and to simplify construction of an electronic part of the whole device, it is better to apply a photodetector with an integrated operational amplifier.

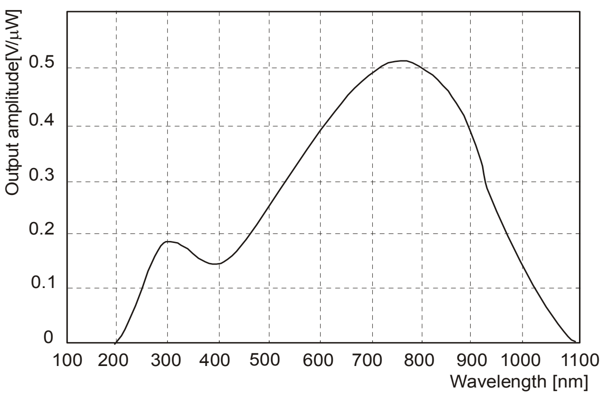


Figure 3. The spectral response of the photodetector applied in the flame monitoring system.

In the signal processing unit, a signal obtained from the photodetector is amplified at an adjustable level. Flame monitoring system is insensitive to interferences of both the adjacent flames and heated up elements of the boiler.

Experimental facility

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.

Diagram of the test rig shown in Figure 4 and Figure 5 shows a view of the combustion chamber.

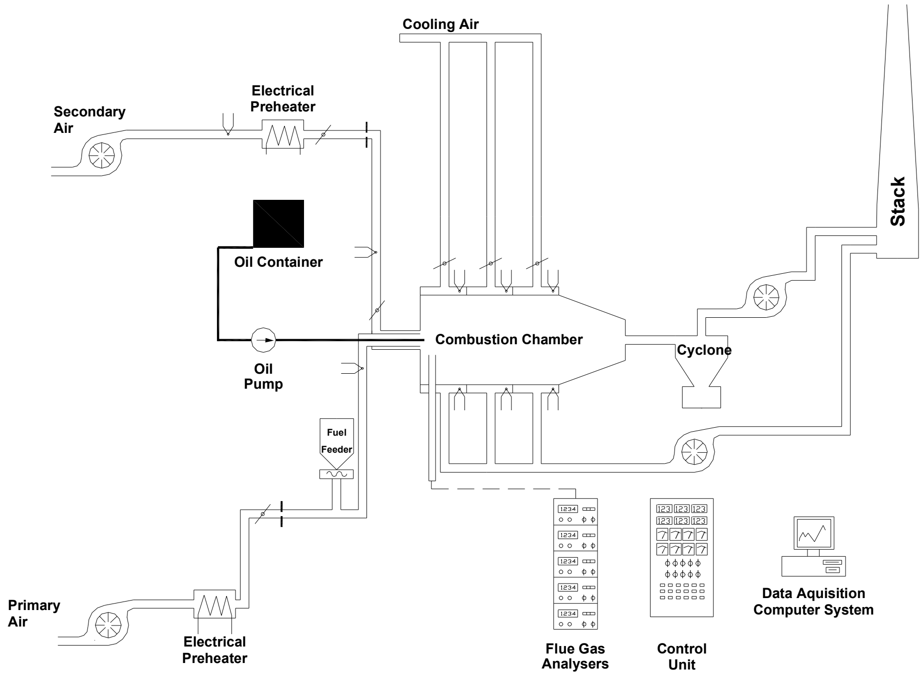


Figure 4. Schematic diagram of the test facility.

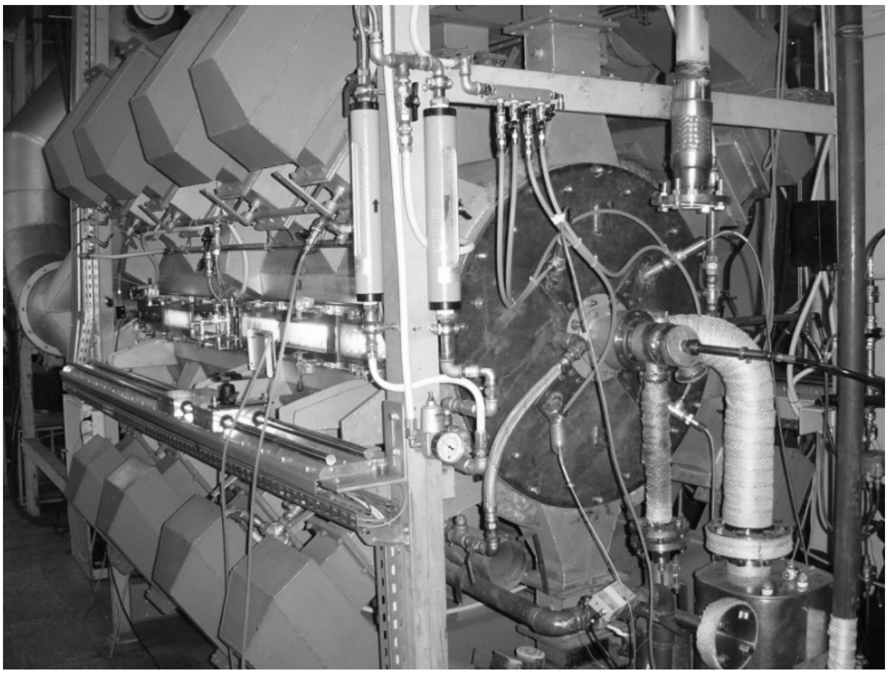


Figure 5. View of the combustion chamber.

The test rig is practically fully computer controlled using dedicated LabView application. It allows setting various air flows, coal feeder speed, air temperatures, flap positions, etc. More than two hundred values are measured: temperatures, airspeeds and flows, fuel flow, flue gas composition (O_2, CO, NO and SO_2) etc.
All the important parameters are stored. The sampling period is 1s system.

The combustion chamber is equipped with fiber-optic probe. Sketch of the chamber with marked areas of view and the view of fiber optic probe placement shown in Figure 6.

a) b)

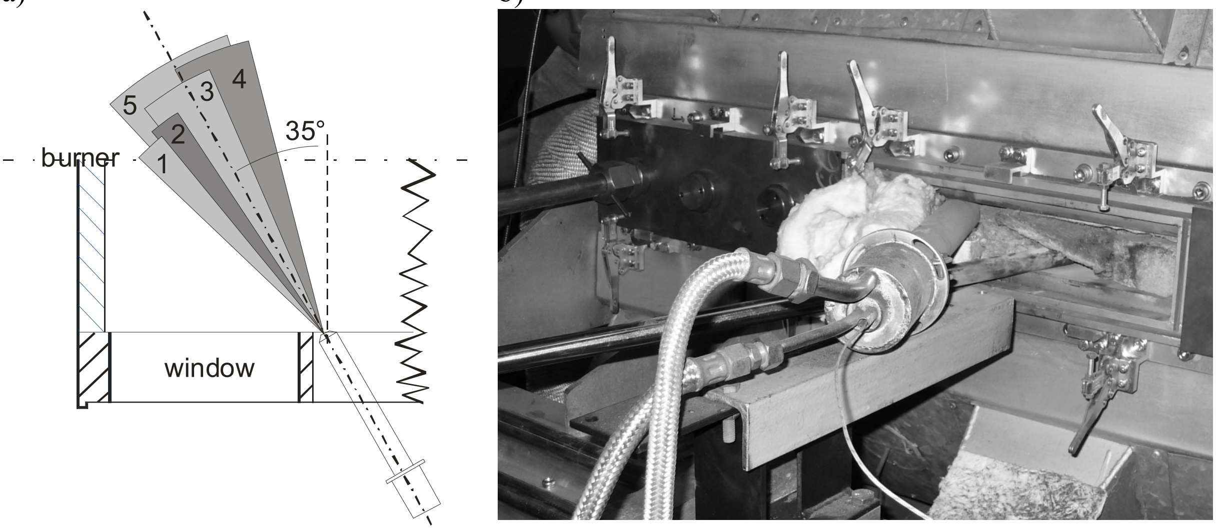


Figure 6. Fields of view of fibers (a) and view the installed probe (b).

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 with changing air and fuel flows. During an individual measurement the amounts of fuel and air are kept constant. A single measurement lasts 300 seconds.

Such method of measurement is to eliminate the impact of the transport delay of gas analyzers. It is assumed that during measurement the conditions are fixed 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

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 [15,16,17].

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 [18]. Figure 7 shows example waveforms of the signal average intensity and the number of zero crossings of signal derivative with changing combustion conditions. The other two mentioned parameters are omitted so as not to obscure the drawing.

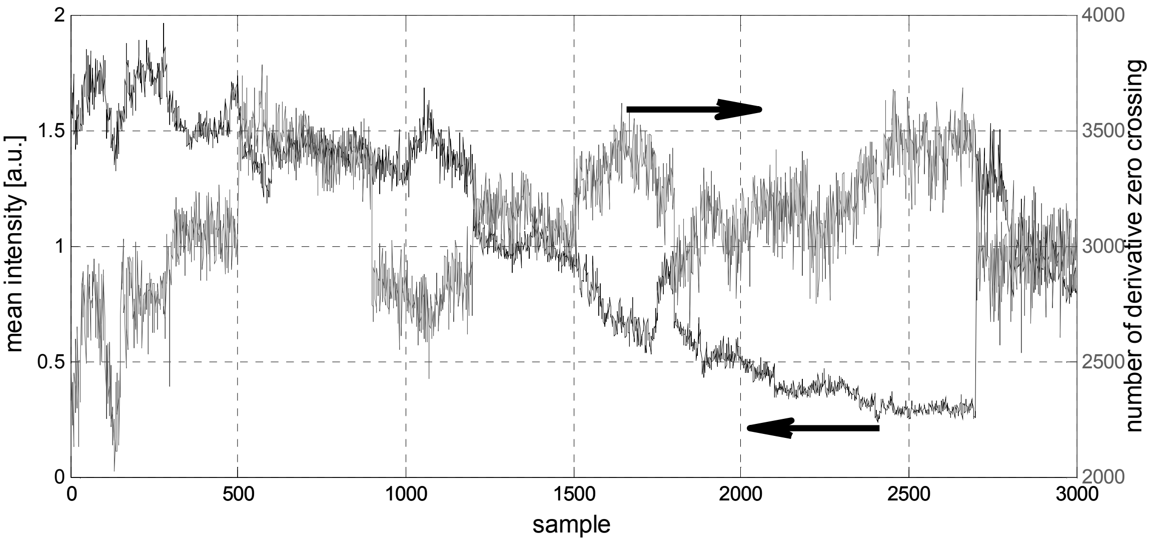
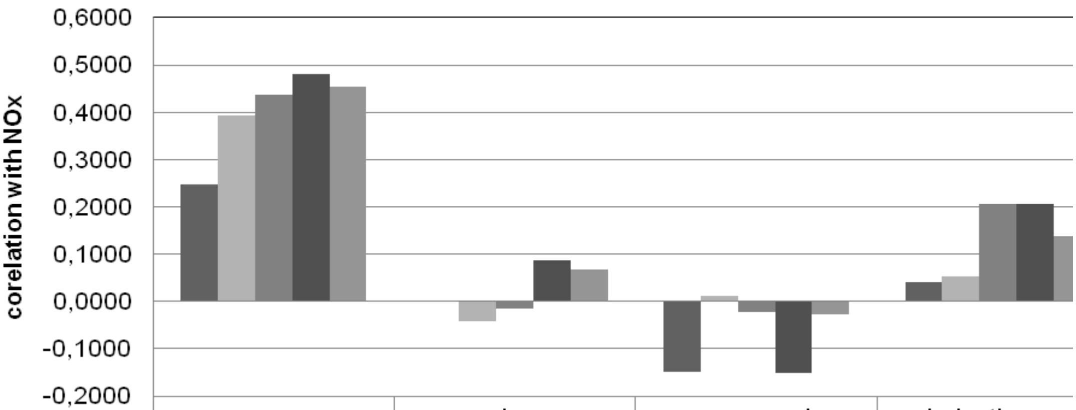


Figure 7. Plot of example time series parameters.

Analysis of models based on all possible combinations of parameters would be too time-consuming. 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 Fig 8.



	mean	variance	mean crossing	derivative z.c.
fibre1	0,2473	0,0019	-0,1498	0,0413
fibre2	0,3941	-0,0419	0,0124	0,0518
fibre3	0,4363	-0,0141	-0,0222	0,2063
fibre4	0,4806	0,0882	-0,1522	0,2051
fibre5	0,4549	0,0667	-0,0270	0,1374

Figure 8. Correlation of NOx emission with basic time series parameters.

The analysis of the correlation shows:

- There is a fairly strong correlation between the NOx emission and mean intensity for fibres 2 to 5, for fibre 1 it is much less significant.
- NOx emissions and the variance of the optical signal are virtually uncorrelated. For all fibres, the correlation value is less than 0.1.

- Correlation between the magnitude of NOx emissions and the number of mean value crossings is very weak, only for fibres 1 and 4 is slightly greater than 0.1
- Emissions of NOx and the number of zeros of the optical signal derivative is moderately correlated for the fibres 3 and 4, a bit worse for fibre 5, and, there is virtually no correlation for fibres 1 and 2.

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 another reason. The average intensity may be dependent on the state of the optical path, for example contamination 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, 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 fiber 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.

Due to the strategy of measurements the data was grouped in distinct centers so the fuzzy rules were generated by subtractive clustering.

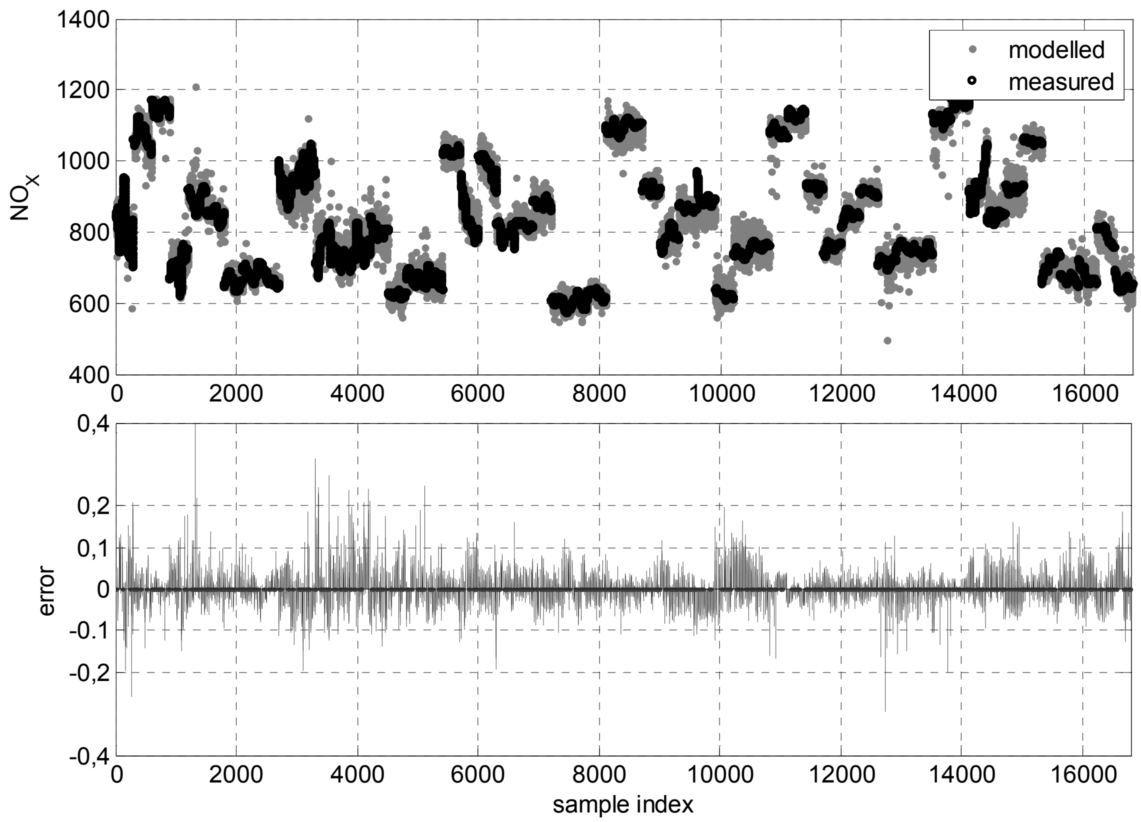


Figure 9. Sets of values measured and calculated on the basis of optical signals (above) and a set of corresponding modeling error.

Tests using all 20 parameters were performed as a reference. Figure 9 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 1 contains parameters of the model errors of nitrogen oxide emissions, using all 20 parameters for different number of membership functions.

Table 1. Error characteristics for NOx emissions model using all 20 parameters.

error parameter	Number of membership functions					
	6	12	19	27	43	56
minimum	-0.3477	-0.4419	-0.3358	-0.4419	-0.3765	-0.2949
maximum	0.6298	0.4986	0.4212	0.4986	0.3493	0.4057
mean value	0.003947	0.002764	0.00204	0.002764	0.001335	0.001217
std. deviation	0.06472	0.05377	0.0461	0.05377	0.03764	0.03548
err>10%*	6.51%	4.05%	2.80%	2.22%	1.55%	1.26%

* 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 vitiated 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. These models achieve slightly better accuracy than those based on all 20 parameters. Table 2 shows the parameters of model error for nitrogen oxide emissions using the intensity and the number of zeros of the derivative for different number of membership functions.

Table 2. 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 value	0,002375	0,001596	0,001333	0,00117
std. deviation	0,04992	0,04071	0,03749	0,03416
err>10%*	3,76%	1,85%	1,5%	1,2%

* percentage of errors greater than 10%

In order to further reduce the number of inputs we have examined models using the intensity and the number of signal derivative zeros from fiber 1 to 4 and then 3 and 4. In the first case, the percentage of errors exceeding 10% was 3.15% at 24 membership functions (further increasing their number did not result in a significant decrease in error). In the second case, the percentage of errors in exceeding 10% was more than 9%. 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 [19, 20], while in the case of pulverized coal, this parameter plays a marginal role.

The experiment technique requires modification. The assumption of the strategy of measurements was the constancy of process input and output parameters along the. 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.

Conclusions and remarks

Optical signal can be used for diagnostics of an individual burner. The optical signal is currently the fastest and selective way of getting information about the quality of combustion. Its interpretation, however, poses many difficulties.

The results of the use of modern methods of obtaining information about the quality of combustion (e.g. about NOx emissions) 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 [21,22] 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.

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