W. Wójcik[1], T. Golec[2], I. Manak[3], A. Smolarz[1], A. Kotyra[1], P. Komada[1], M. Kalita[1]
[1]Technical University of Lublin, Department of Electronics, Lublin, Poland,
[2]Institute of Power Industry, Warsaw, Poland,
[3]Belarusian State University, Minsk, Belarus

OPTOELECTRONIC METHOD OF ESTIMATION OF CHOSEN COMBUSTION PARAMETERS OF AN INDIVIDUAL PULVERISED COAL BURNER

There are several tens of burners operating in a power boiler and their control based on averaged and delayed measurements is often not effective enough. The article describes attempts to obtain information about levels of emission of NOx and CO from the signals of the fiber-optic flame monitoring system developed in the Department of Electronics of the Lublin University of Technology. Artificial neural networks are used for estimation of emission. The article contains description of an object and the measurement system as well as results of research of nitrogen oxides and carbon monoxide modelling.

1. 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 cerate 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 carbon dioxide emission below 100ppm as well as contents of unburned particles in ashes below 5%.

The most effective technique of NOx emission reduction is such control of air and fuel to create rich and lean zones of combustion. It leads both to the limitation of synthesis and increase of reduction of already synthesized nitrogen oxides. 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. Reduction of an amount of air in initial zones of combustion may also produce flame instability caused by the deficiency of oxygen near the burner. It may result in lifting-up of the flame or, even worse, flame may be cut-off. These phenomena are undesirable or even dangerous for the boiler. The negative effects of application of low-emissive technology of combustion are limiting the achievable emission reduction. In order to avoid them the low-emissive burners have to be equipped with individual monitoring and diagnostic systems.

In order to minimize 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-pulverized 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]. 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. 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. The solution is the fibre-optic monitoring system developed in the Department of Electronics at Technical University of Lublin.

2. Fiber-optic monitoring system

In industrial burners outlet velocities of an air and a fuel are high enough to make combustion process take place in turbulent flame. It provides indirect information about condition of the burner. Flame turbulence manifests itself, among other things, as pulsation of intensity or flicker. Parameters of this turbulence depend on physical and chemical phenomena proceeding in a flame, therefore it is possible to infer about the course of these phenomena on the basis of pulsation of the flame. The fiber-optic system is designed to observe multiple flame zones in a single burner [2, 3, 4, 7]. Each zone is observed by a single optical fiber which aperture is limited to improve a spatial resolution. An optical signal is fed to a silicon photodetector (in our case it was integrated with a transimpedance preamplifier). Such obtained electrical signal is conditioned in two channels. In linear one a bias is removed so its output signal is proportional to the changes of local intensity of flame radiation i.e. flame flicker. In the second channel a logarithmic amplifier is used in order to cover the whole dynamic range of local flame intensity. According to our experience it may reach even five decades. Output signals from both channels are standardised to bipolar 10V amplitude. Investigation of spatial distribution of flame pulsation and intensity carried out in real boiler allowed to determine zones that are most sensitive to the changes of input signals (amount of primary and secondary air). Experience gained operating the probe in industrial conditions allowed creation of an optoelectronic system for combustion process monitoring that employs flame pulsation as a certain measure of turbulence and its intensity as a certain measure of temperature [3, 4, 5, 6, 7]. This preprocessing is being done on-line using a PC computer. Usage of DSP is planned for future applications. The output signal of this system is practically instantaneous and is not averaged. Schematic diagram of the system proposed for estimation of nitrogen oxides or carbon monoxide using a neural network is depicted at fig. 1.

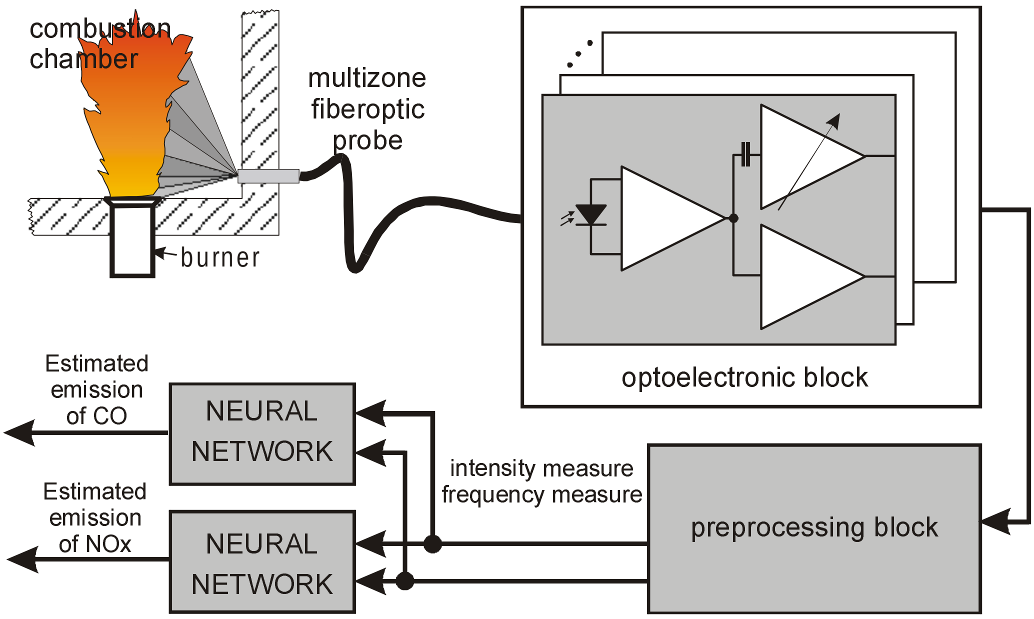

Fig. 1. Optoelectronic system proposed for estimation of nitrogen oxides or carbon monoxide using an artificial neural network

3. Experiments

Experiments were performed on the investigation installation located in the Institute of Power Engineering in Warsaw. The object was chosen because it was well equipped with measurement devices and the possibility of carrying out experiments on a single burner. It consists of a combustion chamber with a single swirl pulverized coal burner made 1:10 scale comparing with industrial one. The mill air, secondary air and coal flows are being measured as well as flame intensity and pulsation. The gas analyzers' probes are located 1m from the burner outlet and in the flue gas duct. Measurements are stored in data acquisition system at sample rate 1 per 10 seconds.

Signals from zone of flame most sensitive to changes in air to fuel ratio were preprocessed to match sampling velocity of optical system and combustion chamber system. Two values were finally utilized:

- intensity measure – understood as mean intensity of a chosen zone of a flame within a sampling period,
- frequency measure – understood as the number of zero hits of a derivative of intensity of a chosen zone of a flame within a sampling period.

The latter one has been chosen because as a certain measure of frequency cannot be directly estimated by a neural network.

4. Estimation of nitrogen oxides emission and carbon monoxide emission

Correlation coefficients between output and input are not very high. For NOx emission they are – 0.09 and 0.34 respectively with intensity measure and frequency measure, while for CO they are 0.56 and 0.38 respectively. Yet, cross-correlation plots give much clearer view on the dependencies, they are normalised so the autocorrelations at zero lag are identically 1.0. It can be seen that for both gases the frequency measure is more regular what means better suitability. Nevertheless, neither measure can be used alone for estimation.

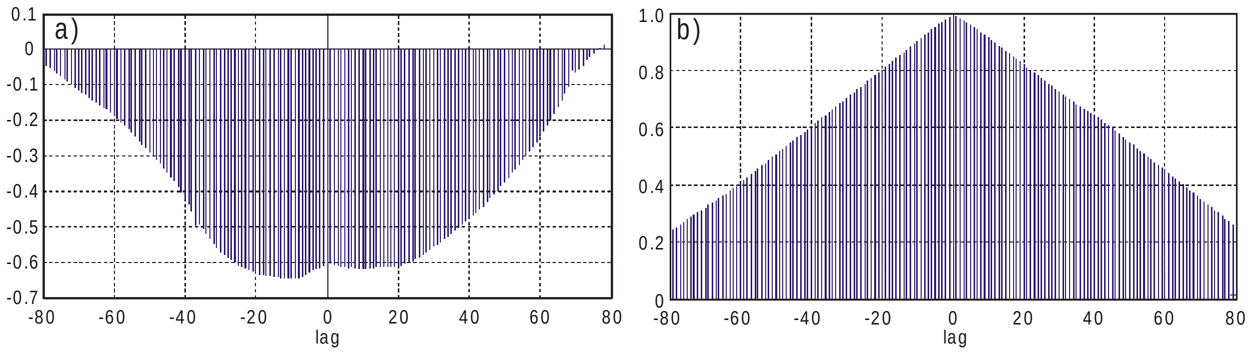

Fig. 2. Correlation of measured NOx emission with: a) flame intensity measure; b) flame frequency measure

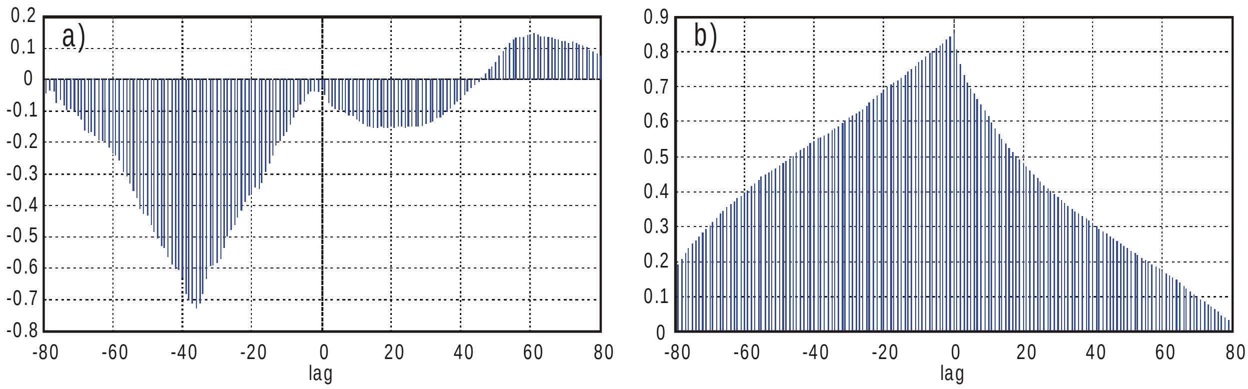

Fig. 3. Correlation of measured CO emission with: a) flame intensity measure; b) flame frequency measure

The neural NOx emission estimator has been built on the base of series of experiments. Utilisation of information obtained from only one flame zone most subjected to the changes in fuel/air ratio has been assumed. A model was considered acceptable when its error was smaller than 10%. The best results were achieved for Neural Network Finite Impulse Response model NNFIR(n_b, n_k) of the following form [8]:

$$y(t) = g\left[\varphi(t), \theta\right] + e(t)$$

where t denotes time, $y(t)$ is model output, θ is a vector containing network weights, g is a nonlinear function realized by the network and $e(t)$ denotes a white noise. The regression vector φ(t) for NNFIR model has the following form:

$$\varphi(\mathrm{t}) = \left[u(t-n_k), \ldots, u(t-n_b-n_k+1)\right]$$

where u is model input and n_b, n_k are model parameters.

According to the previous tests [7] the best results have been obtained for a model NNFIR(5,0) implemented as a multilayer perceptron with a structure MLP(10,4,1). Figure 3 depicts NOx emission level plot recorded during one of experiments together with values obtained from the optical probe and the neural estimator. An error for "opto-neural" estimator of NOx emission is lower than 10% for every sample and its mean value within considered period is about 3%. For the sake of clarity of comparison, both signals were synchronised in order to nullify a delay of gas analyser (the delay has been identified beforehand).

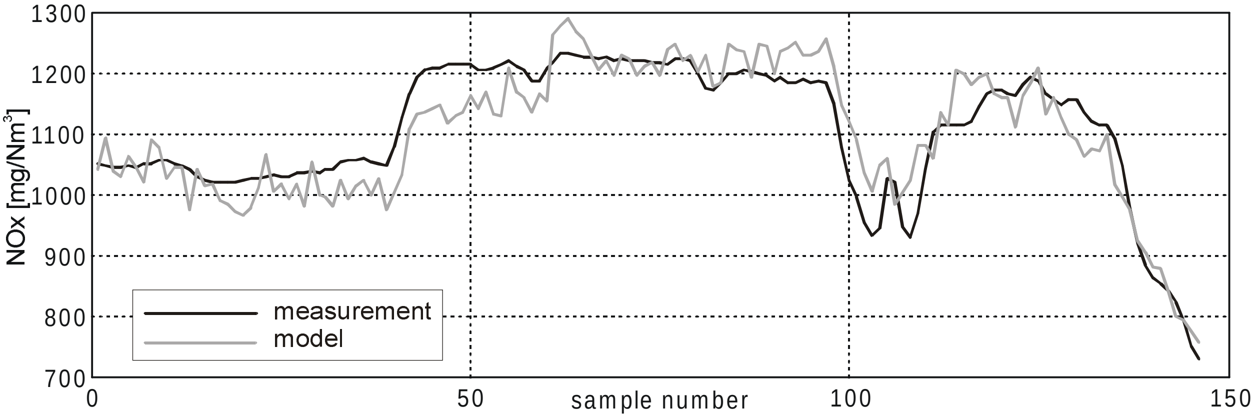

Fig. 4. Plots of NOx emission – measured (black) and estimated on the basis of optical signals (gray).

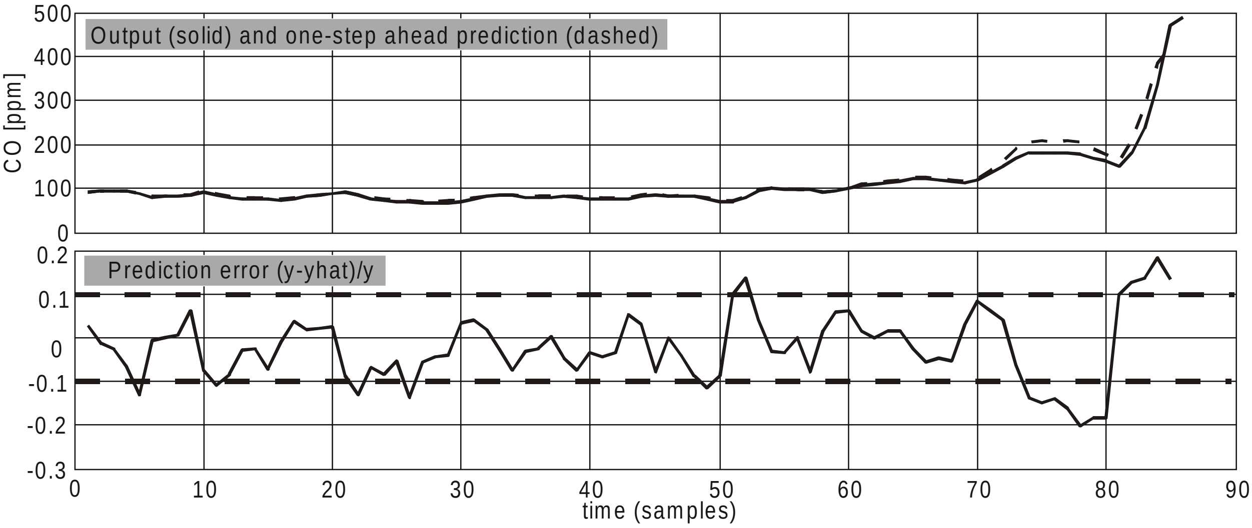

Fig. 5. Estimation of CO emission

NNFIR model has also been used for estimation of carbon monoxide emission and at this stage of development we have found NNFIR(5,1) model implemented as MLP(10,3,1) to be most accurate. Nevertheless the best model achieved does not meet the requirements, especially at high levels of emission. It is probably due to the training set containing a majority of points of low emission. The time plot of both measured and estimated values of CO emission are shown at figure 5 together with a plot of error with 10% boundaries marked.

5. Conclusions

Signals obtained from the optical probe provide fast information about the quality of combustion. Because its output depends on fuel-air mixture composition as well as on flame temperature it also brings information about synthesis of nitrogen and carbon oxides and this is the fastest way to obtain this information. Furthermore, this is the way to obtain information from individual burner, what was impossible to be done with a gas analyser. Results of investigation of the possibility to estimate emission of nitrogen oxides and carbon monoxide on a basis of optical signals with utilization of neural networks seam to be promising. Accuracy achieved for NOx is better than 10%. Unfortunately this is not the case of CO. Although the flame zone frequency measure is strongly correlated with CO emission a model built using this measure only results insufficient. Present, more complex models exhibit sufficient accuracy in the low emission range but at high emissions an error value is unacceptable. The research is being continued. Initial models of NOx were insufficient also, so the authors hope that in the near future better results will be obtained for CO models.

Further research will be focused on:

- experiments at high level of CO emission,
- extension to an industrial multiburner system,
- utilisation of other types of signal preprocessing (e.g. Fourier or wavelet transforms),
- utilisation of fuzzy logic.

1. Arabas J., Białobrzeski L., ChomiakP L., Domański T., Świrski K., Neelakantan R. Pulverized Coal Fired Boiler Optimization and NOx Control using Neural Networks and Fuzzy Logic, proceedings of AspenWorld'97, Boston, Massachusetts, 1997.

2. Wójcik W. The Optical Fibre System for Flame Monitoring in Energetic Boilers, Proceedings of SPIE, Technology and Applications of Light Guides, 1997, vol.3189, pp. 74–82

3. Wójcik W. The utilisation of flame flicker in the fibre – optic system for combustion quality evaluation in industrial energetic boilers, Conference Proceedings EUROSENSORS XI, vol.3, pp. 997 – 1000, Warsaw, 1997

4. Smolarz A., Wójcik W., Kotyra A., Wojciechowski C., Komada P. Fibre optic monitoring system, "Lightguides and their applications", Proceedings of SPIE, vol. 4239, pp.129–132

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, 2001, pp.517–522.

6. Wójcik W., Smolarz A., Kotyra A. Optical fibre system for flame monitoring in power boilers, Proceedings on 2–nd International Symposium on „Microelectronics Technologies and Microsystems", pp.102–108, Lviv, 1998

7. Wójcik W., Kotyra A., Smolarz A., Komada P. Optical fibre system for combustion quality analysis in power boilers, Proceeddings on International Conference on Optoelectronic Information Technologies, „PHOTONICS-ODS 2000", 2 – 5 October, pp. 181 – 187, Vinnytsa, Ukraine, 2000

8. *Norgaard M. Neural Network Based System Identification Toolbox, Tech.Report. 00-E-891, Department of Automation, Technical University of Denmark, 2000.*