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NEURAL NETWORK CONTROLLER FOR INDIVIDUAL PULVERISED COAL BURNER

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Burning pulverised coal in power boilers causes considerable emission of atmospheric pollution. In order to decrease it the combustion process itself has been modified, however at cost of side effects like: increased level of unburned coal particles in the ashes. There are tens of burners in a single power boiler and emission level measurements are made in flue gas duct, so the control based on such averaged and heavily delayed values often results ineffective. The neural controller of the pulverised coal burner attempts to resolve these problems. The clue is utilisation of fibre-optic system for monitoring of chosen zone of flame developed in Department of Electronics of Technical University of Lublin in subordinate control loop. The article contains description of controlled system and optical fibre measurement system as well as the idea and simulations of new control method.

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 carriers of primary energy. Power industry and coal based especially has its important share in air pollution. 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 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 NO_X. Their synthesis and transformations depend on many factors, some of which can be effectively changed by modification of operation conditions of each burner and of the whole furnace system. The main advantage of such modifications is the reduction of NO_X at relatively low investment cost.

2. MEANS TO DECREASE EMISSION OF NITROGEN OXIDES

The low-emissive burner should not only assure limitation of NO_X 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 following means can be used in order to decrease emission of nitrogen oxides:

- reduction of combustion temperature,
- modification of air distribution,
- modification of combustion aerodynamics,
- utilisation of reduction properties of a rich flame.

In case of pulverised coal possibilities of reduction of combustion temperature are rather limited because of the threat of loss of stability of the flame.

The most effective technique of NO_X 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 synthesised nitrogen oxides. Unfortunately, reduction of NO_X 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,
- decreased heat transfer efficiency.

Moreover, reduction of an amount of air in initial zones of combustion may produce flame instability or even worse flame may be cut-off. These phenomena are undesirable or even dangerous for the boiler. These negative effects of application of low-emissive technology of combustion are limiting the possible to achieve emission reduction. Yet, they can be at least partially overcome thanks to the knowledge of processes being carried out in the boiler furnace and its application at the stage of design as well as operation of burners and boilers.

3. FIBRE-OPTIC MONITORING SYSTEM

In industrial burners air and a fuel outlet velocities are high enough to make combustion process take place in turbulent flame. It causes additional problems for measurement yet, at the same time 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.

Processes proceeding in a pulverised coal turbulent flame are very complex and at the present time there is no satisfactory mathematical model that describes them. It is not possible to formalise (mathematically describe) relation between input values and flame pulsation, although such relation exists, what has been confirmed in series of studies and articles by our research team, it can be therefore used for evaluation of combustion quality. The fiber-optic system developed in the Department of Electronics at Technical University of Lublin is designed to observe multiple flame zones in a single burner [1,4,5,6]. 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 [4]. 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).

4. NEURAL NETWORK CONTROLLER FOR PULVERISED COAL BURNER

As it was mentioned the low-emissive combustion leads to series of problems. In order to minimise their consequences it is necessary to obtain information about the course of combustion process as well as its adequate control. This task is relatively difficult because of high complexity of phenomena proceeding during the 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, NO_X). 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 for several power units collectively). The delay is nonstationary and can reach even several minutes so the control often results ineffective. There are also successful attempts of replacement of classic controller with a neural network one [2]. None of these solutions offer the possibility to closed-loop control of individual burner, basically because of the lack of suitable measurement methods.

The artificial neural network controller of the pulverised coal burner, described in the article, attempts to resolve these problems. Combustion process is extremely complicated and non-linear. This is the reason why neural networks were applied. They are suitable for description of phenomena where an exact law describing dependencies is unknown or insignificant. Nevertheless, the clue is utilisation of fibre-optic system for monitoring of chosen zone of flame developed in Department of Electronics of Technical University of Lublin. The output signal of this system is practically instantaneous and is not averaged.

4.1. CONTROLLED SYSTEM

Design work is being carried out on two systems simultaneously. First one is the research boiler system located in Institute of Power Industry in Warsaw. It is a combustion chamber with a single swirl burner that is a 1:10 scale model of industrial burner. The lab stand allows accurate measurements of all significant values: airflow to the burner (3 streams), coal flow, various combustion chamber temperatures, gas constitution about 1m from the burner and in a flue gas duct. This system is used for initial tests, which are subsequently verified on an industrial system: OP650 type boiler of 200MW power unit in “Kozienice” Power Plant S.A. The boiler is fuelled with pulverised carbon. There are four carbon mills. Swirl burners are installed on one of boiler’s walls in four rows, six burners each. OFA nozzles are installed on the opposite wall. Burners and OFA nozzles are equipped with servo drives that enable remote adjustment of the flow. Flue gas analysers (O_2, CO, NO_X) are installed in flue ducts behind air heat exchangers. Unit efficiency is calculated using specialised software. The unit is controlled by distributed data acquisition and control system WDPF of Westinghouse.

4.2. THE IDEA OF CONTROLLER

The idea of controller is depicted on figure 1. It will work in subordinate loop, correcting values set by existing superordinated system.

During the tests only the flame pulsation and flame intensity were used as controller input. The controlled value is an air to fuel ratio. Such variable set was chosen to reduce the system dimensionality. It is difficult to determine now which set of variables will be the best. Neural networks are not able to learn frequency dependencies directly. The input has to be pre-processed. This is the reason why the flame pulsation, as a frequency domain value, was used as controller input.

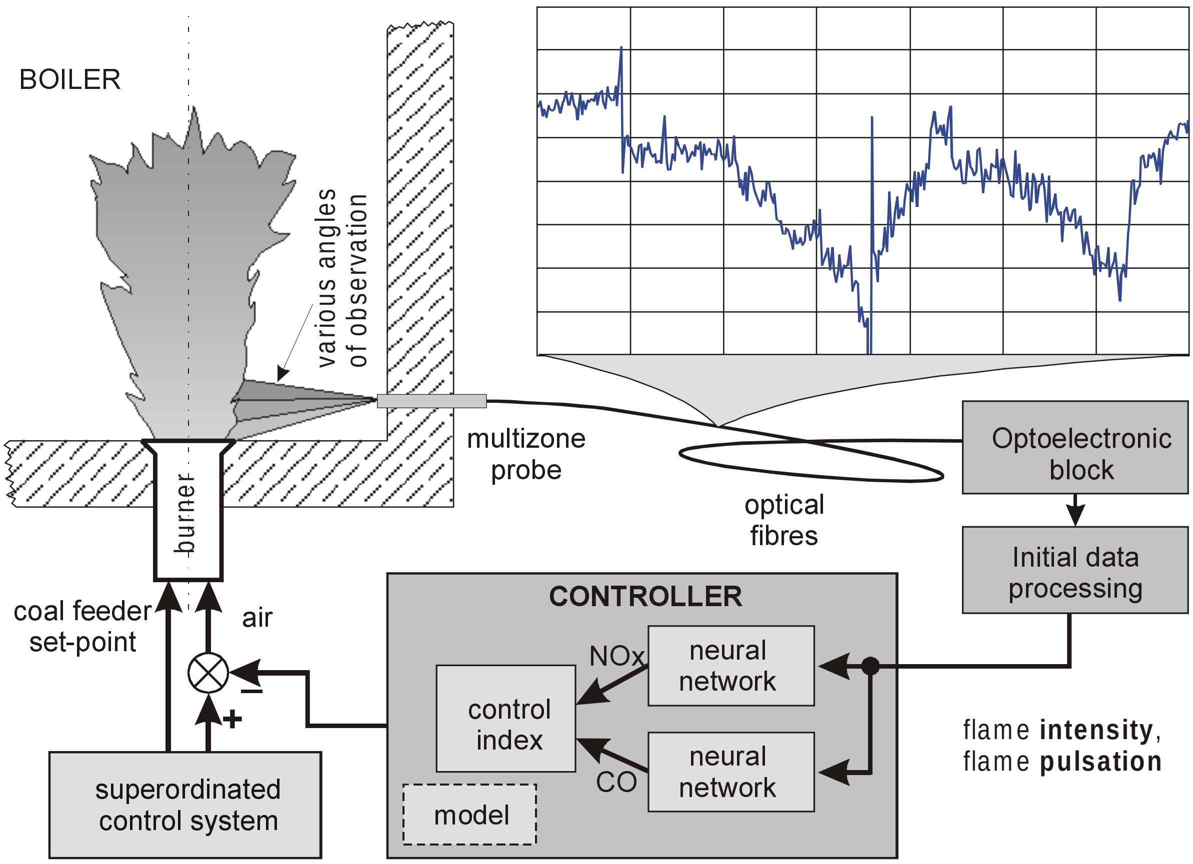

Fig. 1. Idea of controller for pulverised coal burner

Initially assumed goal of control is minimisation of emission of nitrogen oxides. Yet such criterion is insufficient because NOx concentration decreases monotonically for decreasing amount of oxygen (fig. 2). At certain low level of oxygen an increased level of unburned particles in ashes appears as well as unacceptable level of carbon oxide in flue gases. It leads to drop of boiler efficiency – main economical factor of its exploitation. Besides, an increased level of unburned particles in ashes disqualifies it as construction material additive because of reduced strength. Considering this we can construct control quality indicator as minimisation of NOx with penalty when the level of unburned particles in ashes exceeds acceptable limit. Yet frequency of determination of unburned particles level presents a problem – samples are gathered every several hours. The level is however correlated with emission of carbon oxide though increased level of unburned particles appears earlier. Therefore in initial trials CO emission can be used as penalty factor and level of unburned particles can be used for verification only.

Finally, in order to construct the internal model and control quality index, we need to identify NOx and CO emission processes.

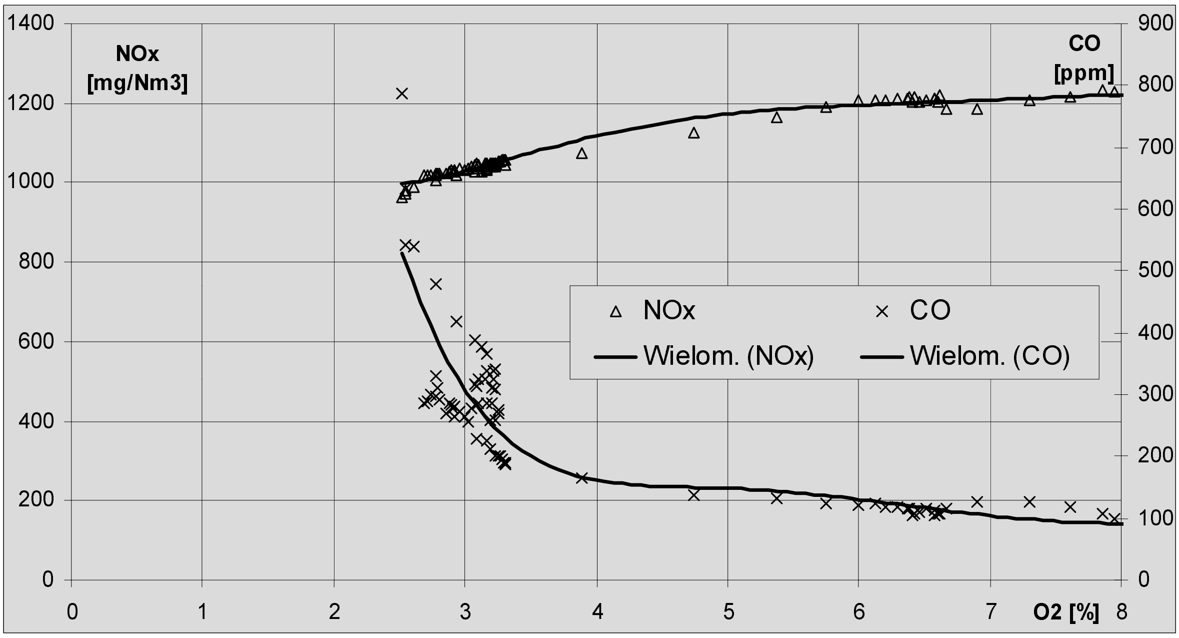

Fig.2. Plot of nitrogen oxides (upper) and carbon oxide (lower) emission as a function of oxygen concentration in flue gasses. Measurements were made on laboratory system in Institute of Power Industry in Warsaw

4.3. IDENTIFICATION OF NO_X EMISSION PROCESS

In the recent investigation of the research team it was proved that parameters of flame flicker depend on the burner input. Yet, the knowledge of a quantitative dependence between flame flicker parameters and emission of NO_X and CO is necessary to build the controller. The “Matlab” and Statistica” packets were used for process identification [7]. Initial tests made with linear models presented insufficient accuracy, with FPE exceeding 10% for the best model [3]. The nonlinear neural equivalents of autoregression as well as mixed autoregression and moving average were used for process identification then. Nonlinear RBF and MLP networks with logistic activation function were used for tests.

Nonlinear counterparts to the popular linear models have generally the following form:

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

or on predictor form:

$$\hat{y}(t\,|\,\theta) = g\left[\varphi(t,\theta),\theta\right],$$

where t denotes time, $y(t)$ is output, $\varphi(t,\ \theta)$ is regression vector, θ is a vector containing the weights, g is the nonlinear function realized by the neural network and e(t) is a white noise signal that is independent on past inputs.

The simplest is NN-FIR (Finite Impulse Response) model considering past inputs only. The regression vector has the following form:

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

where $u(t)$ is the input vector, n_a, n_b, n_k are model parameters.

The NN-ARX model contemplates past inputs and observed outputs and the regression vector has the following form:

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

The NNOE model contemplates past inputs and output predictions and the regression vector has the following form:

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

The NN-ARMAX model contemplates past inputs, output predictions and residuals and the regression vector has the following form:

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

where ε is the prediction error $\varepsilon(t) = y(y) - \hat{y}(t|\theta)$.

A system with poles cannot be described exactly by NN-FIR-model of finite order. However if the system is stable and the impulse response decays reasonably fast the system can often be approximated well this model. NN-FIR and NN-ARX models do not contain feedback, therefore they are always stable. NN-OE and NN-ARMAX contain feedback and they are usually referred to as recurrent networks. It is quite difficult to analyze their stability properties. It might be that they are stable in some regimes while unstable in others, so it is relevant to consider the stability as a local property [7].

The results of comparison of different networks like the radial basis function (RBF) and the multilayer perceptron (MLP) of the same order show that although RBF has lower maximum error – 0.04 for RBF and 0.65 for MLP, the rms error is higher – 0.46 and 0.06 respectively. The correlation is also better for MLP – 0.998 (0,88 for RBF). Further investigation will be carried out considering three layer MLP only.

Figure 3 depicts example results of NO_X modelling for laboratory burner from Institute of Power Industry in Warsaw. Flame intensity and flame pulsation are inputs for NNFIR(10,1) model. Similar results are obtained for other gases that have to be considered in the controller: carbon dioxide and oxygen concentration in flue gasses.

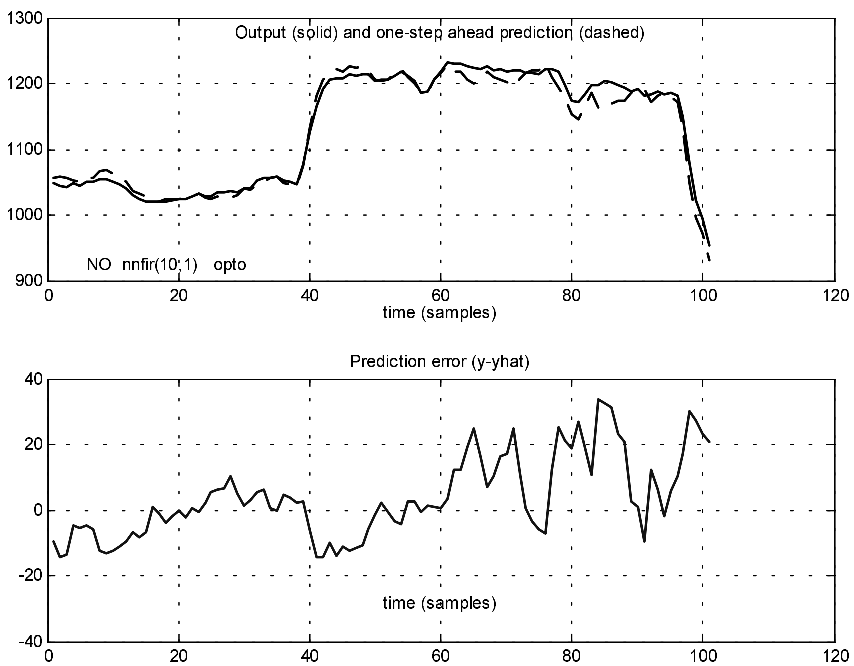

Fig. 3. Results of identification of NOx emission with optical probe signals as input

4.4. Simulation tests of the controller

Initial tests were made using the simplest PI controller and their aim was to check the possibility to stabilise NO_X emission at determined level. The step change of air to fuel ratio was selected as a disturbance. The closed loop system response was measured. Figure 4 depicts simulation results made for burner from the Institute of Power Industry in Warsaw. As it can be seen the controller operates correctly. For the sake of comparison NO_X output from the burner was plotted with dashed line. It was advanced by the gas analyser delay time to make comparison easier. Steady state error does not exceed 5 %.

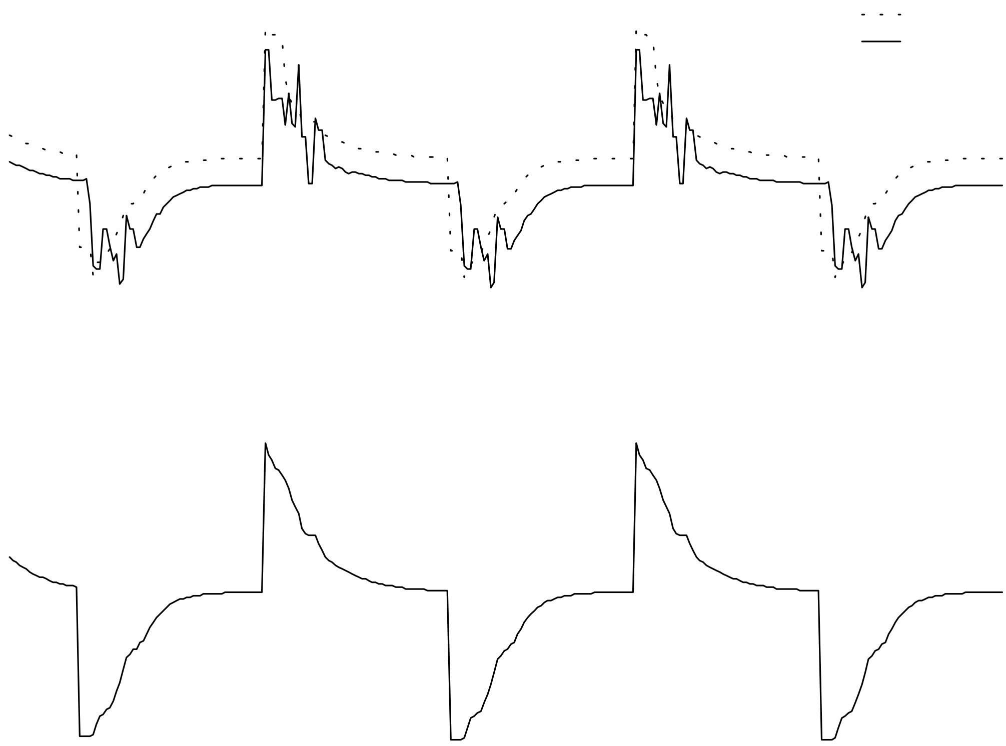

Fig.4. Closed loop response for step change of air to fuel ratio

5. CONCLUSIONS

The utilisation of the optical probe provides fast information about the quality of combustion. Because output of the optical probe depends on fuel-air mixture composition as well as on flame temperature it also brings information about synthesis of nitrogen oxides and this is the fastest way to obtain this information.

Application of the neural network is effective when analytical model of the process is too complicated or unknown and analytical identification of the system is not important, but only its input/output. Networks ability to generalise is also valuable. Initial results of neural identification of synthesis of NO_X and other flue gasses on a basis of output of the optical probe indicate that such model error is smaller than 5 %, presumably further research will allow its reduction.

Initial tests made using simple PI controller with "optical" signals as input indicate that it is possible to stabilise the emission of nitrogen oxides at desired level. The utilisation of optical probe makes the system operate properly even when the disturbance is caused by for example primary air density change due to increased humidity in the coal. It happens frequently in winter season. It is not possible to contemplate such disturbance in currently used controllers.

The future step will be application of fuzzy logic because the combustion is a process that cannot be analytically described and furthermore quantitative rather than qualitative interface is more convenient for the maintenance staff.

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