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Application of fibre-optic flame monitoring systems to diagnostics of combustion process in power boilers

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Abstract. In this work problems associated with requirements related to pollution emissions in compliance with more restrictive standards, low-emission combustion technology, technical realization of the monitoring system as well as algorithms allowing combustion process diagnostics are discussed. Results of semi-industrial laboratory facility and industrial (power station) research are presented as well as the possibility of application of information obtained from the optical fibre monitoring system for combustion process control. Moreover, directions of further research aimed to limit combustion process environmental negative effects are presented.

Key words: pulverised coal, combustion, combustion monitoring, signal processing, process diagnostic, combustion process control.

1. Introduction

Burning fossil fuels, which are the main carriers of primary energy, is the greatest source of atmospheric pollution. This general rule applies especially to Poland as within a horizon of 50 years fossil fuels will be a basis for energy production processes. It is therefore necessary to make efforts allowing to decrease environmental nuisance of combustion processes. Currently in Poland 97% of electrical energy is being obtained by burning the coal what in turn results in progressive environment deterioration.

Current trends in European Community economy force limitation or elimination of environmental impact, imposing very strict requirements, among others on power industry. Meeting these requirements is to be very difficult and expensive. Additionally, the active primary and secondary frequency and power control regime of the power unit forces continuous power variation within the assumed band of power adjustment in order to meet the requirements of the Power Dispatch Centre (PDC) and the Union for the Co-ordination of Production and Transmission of Electricity (UCPTE). Such conditions impose particularly tough requirements for power unit control devices, systems and circuits, which have to ensure both adequate dynamics within the assumed band of power adjustment and appropriate combustion conditions. For this reason the combustion process control that meets requirements of PDC, UCPTE and environment protection is a very difficult and responsible task. Research and analyses of the combustion process in power boiler together with new designs of technology equipment allowed to make an effort to resolve the problem of nitrogen oxides (NOx) emission limitation without carbon monoxide (CO) emission increase by the method of adequate organization of combustion process. The method, admittedly, does not offer such radical NOx emission decrease as catalytic methods, yet it requires incomparably lower capital expenditure. Apart from the modification in the technology equipment, the condition to obtain permanent results is an adequate control of the combustion process.

Hitherto prevailing solutions preferred the follow-up control of air amount following the amount of coal with superordinated correction of free oxygen (O_2) contents in flue gasses. Such control unfortunately does not assure obtaining adequate instantaneous values of parameters, although frequently in terms of mean values is apparently satisfactory. Besides, not enough attention is being paid to decreasing efficiency which results in necessity to burn additional fuel (pulverised coal) what in effect causes global increase of emission of substances harmful for the environment.

Despite implementation of digital control based on process variables along with delayed and averaged concentration measurements of chosen components of flue gasses, present national standards (Ministry of Environment Decree from 30 July 2001) are met with difficulties. The European Commission directives restricting emission standards will be introduced between 2008 and 2012 and in 2013 will become obligatory. They will cause a necessity to change presently used control systems, which should be complemented with effective diagnostic systems. For this reason large research groups from European Union as well as from the USA and Japan are intensively working on this problem. Therefore, it has to be underscored that the subject matter carried out by the author's research team in cooperation with Thermal Processes Department of Institute of Power Engineering in Warsaw is important and up-to-date. The results obtained allow an effective international cooperation with Germany, Spain or Wales from one side and Russia, Ukraine or Belarus from the other.

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2. Low-emission combustion techniques

Principal pollutants resulting from a combustion process are as follows:

- carbon dioxide (CO_2),
- sulphur dioxide (SO_2),
- nitrogen oxides (NO_x).

Reduction of emission of carbon dioxide originated in a combustion process is a very difficult task considering that all fossil fuels contain carbon. The most effective method of its emission reduction is the rationalization of energy consumption e.g. by application of energy-saving technologies or improvement in electrical energy production with the use of combustion process.

Sulphur oxides significantly contribute to the atmospheric pollution causing acid precipitation, acidifying soil and water bodies which leads to the negative environmental effects (soil fertility decrease, impoverishment or even extinction of plant and animal life). Moreover, their corrosive properties cause serious problems in operation of boilers and turbines. Because the atmospheric persistence time vary from 24 hours to 4 days, they can move at considerable distances, so the pollutant budget for a given state has to consider the "imported" and "exported" sulphur dioxides. Reduction of SO_2 emission is obtained in special desulphurization plants.

The nitrogen creates oxides from NO to N_2O_5, yet only three of them may be originated in combustion process: N_2O, NO and NO_2. They are of various properties, however N_2O is not a toxic gas and it is used in medicine as an aesthetic. Combustion process generates mostly the nitrogen monoxide NO and a small amount of nitrogen dioxide NO_2. In the combustion technology the NOx term is used to denote the mixture of the above oxides (as a sum $NO+NO_2$ converted into NO_2). Nitrogen oxides (NOx) play the most important role in air pollution at local scale resulting in acid precipitation, photochemical smog or ozone depletion.

The NOx emission reduction in combustion process may be obtained by actions undertaken:

1) in a boiler,
2) behind a boiler.

In the first group we can distinguish:

- low-emission combustion technologies, the so-called primary methods,
- methods in which additional reducing components (e.g. ammonia or carbamide) are introduced into a boiler.

In the second group NOx removal from flue gasses is made by selective (SCR) and non-selective (NSCR) catalytic reduction as well as with the use of absorption methods [1]. These methods are used to be called the secondary methods.

In spite of the lowest effectiveness of NOx reduction obtained with the use of primary methods, for the economic reasons they have become most widespread.

We may say that the low-emission combustion technique consists in such organization of the process which assures lower emission of NOx in comparison with the conventional combustion system. It may be implemented by the following means:

- combustion temperature decrease,
- modification of air distribution,
- modification of combustion aerodynamics,
- utilization of reducing properties of a rich flame.

In case of pulverised coal combustion the temperature decreasing is limited by a possibility of loss of process stability. The most effective way to reduce NOx emission is such operating of air and fuel amount to create reach and lean zones of flame, with properties of lower generation and reduction of nitrogen oxides. In spite of certain threat of loss of process stability when burning coal, the temperature decreasing is being used for NOx emission reduction. The result is more visible in case of a hard coal then a brown one [2].

The relationship of NOx emission and air excess in a combustion process is relatively complex and depends on some factors, first of all on flame type and contents of the so called fuel nitrogen N_F. In flames with high air excess ($\lambda > 1$, lean flame) the fuel nitrogen quickly oxidizes to NO_x, while in flames with air deficiency ($\lambda < 1$, reach flame) N_F in great measure converts into N_2. This method is effective in case of pulverised coal (PC) boilers, in which reduction of O_2 in flue gasses behind the boiler results in reduction of NO_x concentration in flue gasses. However since there is a risk of incomplete combustion, slagging and corrosion, the possibility to reduce NOx emission using this method is limited to about 15% [1].

Low-emission combustion with air-staging consists in division of combustion zone into two zones:

- reach ($\lambda < 1$),
- lean ($\lambda > 1$).

In the first one combustion with oxygen deficiency takes place, that is a reduction zone with additionally reduced temperature forms. In the second one an afterburning with controlled air excess takes place. The residence time of burning particles of coal is much longer in the first zone than in the second one and additionally, partial cooling of combustion and intermediate products takes place there. It is schematically depicted in Fig. 1.

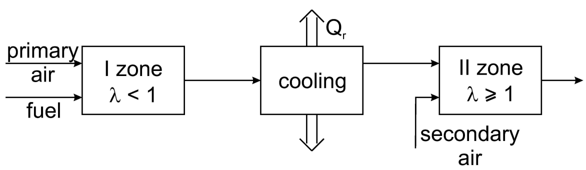

Fig. 1. Low-emission combustion with air staging

This method has the biggest influence on the degree of NOx reduction in case of combustion of fuels containing bound nitrogen and has become the fundamental technique of low-emission combustion in PC fired boilers.

A simplified mechanism of fuel NOx creation and reduction in the reach zone of combustion is shown in Fig. 2 [1, 3].

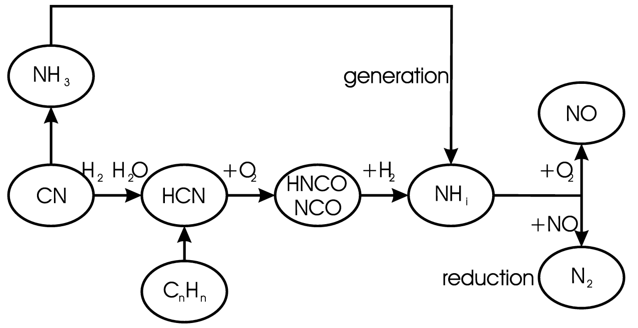

Fig. 2. Dominant mechanism of fuel NOx creation and reduction in the reach pulverised coal flame

During the thermal decomposition of fuel, also the fuel-bond nitrogen is converted into CN decomposition volatile products i.e. simple nitrogen compounds. Among them hydrogen cyanide (HCN) and ammonia (NH_3) predominate. They are flammable do in the presence of oxygen may oxidize to NOx. In the reach zone, because of oxygen deficiency a considerable fraction of HCN and NH_3 is converted into N_2 as well as into nitro and amino radicals (N, HN, NH_2), which are capable to reduce NOx.

An active role of hydrocarbon radicals CH present in a combustion zone at high concentration has to be emphasized. They have a big capacity to reduce NOx, but unfortunately one of the products is HCN. In the second zone (afterburning) there is a slight excess of oxygen, so HCN and NH_3 originated in the first zone are oxidized to NOx.

The effectiveness of emission reduction obtained in the method of air staging is conditioned by the conditions existing in the first, reach zone. First of all they are [1]:

- residence time, which should not be shorter than 1 second (considerably depends on boiler capacity,
- air excess ratio λ_I, which should stay between 0.7 and 0.8 (higher air excess results in increased NOx generation in the first zone and lower than 0.7 results in increasing share of HCN and NH_3 in the first zone, which in the second one are oxidized to NO_x).

Application of the low-emission combustion technologies also causes some side-effects like:

- corrosion under low-NOx firing conditions,
- increased amount of unburned particles in ash and slag,
- increased CO share in flue gasses,
- unfavourable changes in heat distribution in boiler (secondary steam underheat),
- increased slagging,
- increased erosion of burner system,
- increased burners' wear,
- deterioration of combustion stability.

In spite of the above disadvantages low emission technologies are commonly applied and the current research directions tend to minimize costs arisen as a result of application of these technologies.

3. Fibre-optic combustion process monitoring system

A series of factors decide about the course of the combustion process. One of the most important are:

- character of air-fuel flow through the reaction zone (laminar or turbulent), which has the fundamental influence on mass, heat and momentum exchange processes,
- the degree of fuel and oxidizer intermixing at the entrance to the reaction zone. Two extreme cases are usually assumed i.e. when fuel and oxidizer are premixed (kinetic combustion) and when mixing occurs simultaneously with the reaction (diffusive combustion).

In the industrial conditions fuel and oxidizer generally are not precisely mixed in a burner. They are usually fed in a form of the so called primary air (fuel, pulverised coal usually mixed with small amount of air allowing its transportation in pulverised coal ducts and burner itself) and the secondary air (the rest of air essential for combustion). The amount of primary air and secondary air are usually not enough for complete combustion therefore an additional air called OFA or SOFA is introduced to the afterburning zone that allows oxidation to CO_2. Unfortunately during such process a complete combustion is not achieved and the content of unburned particles reaches even 5%.

Usually in industrial combustion of pulverised coal burners dimensions as well as velocities are large enough that the flow is turbulent already at the burner outlet. Instantaneous values of parameters of such flow are not constant in time but oscillate around the mean values. Combustion process control is difficult in such conditions. Presently there is no direct measurement of primary air supplied to a burner what often leads to inhomogeneous distribution between burners supplied from a common duct (three burners for example). In such situation, systems for monitoring of individual burners gain significant importance, becoming an important step towards more effective process control. Several solutions may be applied: those using picture guides and CCD cameras allowing showing chosen combustion zone at the monitor screen, systems analysing free radicals in chosen combustion zone and optical or fibre-optic systems for evaluation of burner operation based on variation of luminosity both in amplitude and in frequency domain in chosen combustion zone. The fibre-optic solution that has been chosen allows simultaneous analysis of several zones of flame as well as assures galvanic and thermal insulation of electronic conversion circuits. It has to be emphasized that the optical fibre probe is installed inside a combustion chamber, in hard conditions such as temperature above 450°C, dustiness or vibration.

In the analysed solution, which scheme is depicted in Fig. 3 and industrial installation at photos in Fig. 4 and Fig. 5 the optical fibre probe may be installed at angle $\alpha \in \langle 5°, 90° \rangle$ to the burner axis. It allows monitoring and diagnostics either wall mounted or tangential burners (Fig. 6). Of course technical solutions are different in each case.

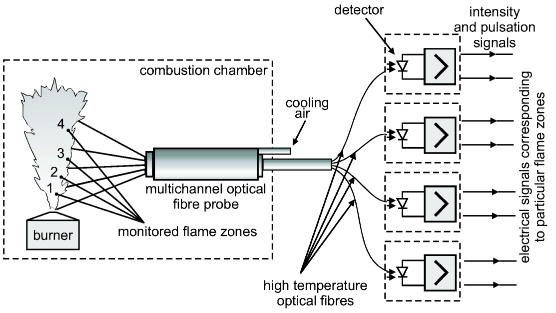

Fig. 3. Block diagram of the flame monitoring system

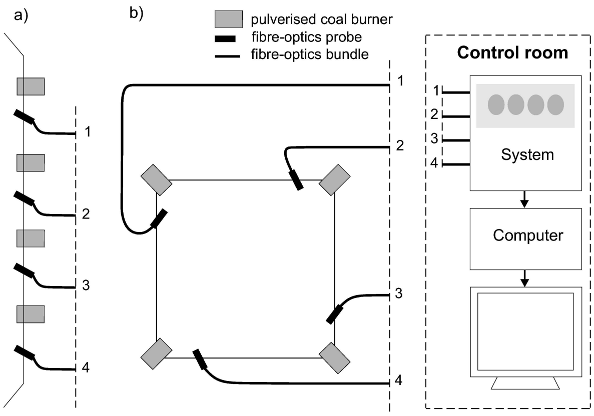

Fig. 4. Optical fibre probe mounting in power boiler

Fig. 5. The optical fibre probe with optoelectronic block

Fig. 6. Fibre probes mounting for: a) wall burner, b) tangential burner

Because the measuring probe is directly placed inside a combustion chamber it was necessary to solve the following problems:

- cooling of the probe,
- protection of fibres against the hot particles,
- cleaning in order to assure uninterrupted optical transmission, maintenance not more frequent than every two weeks.

Cooling ceased to be a trouble spot after application of high temperature fibres which can withstand continually up to 700°C. Protection of fibres against the hot particles is assured by an additional quartz diaphragm (better effects can be obtained using much more expensive sapphire diaphragm).

Assuring maintenance-free operation during one month resulted to be the most difficult task. Special cleaning air was used for this purpose. Nevertheless because of big difference in temperatures of this air and the combustion chamber gas slagging appeared resulting in necessity of relatively frequent cleaning (every several days).

Despite of not completely solved maintenance-free operation of the probe two tasks were executed in parallel i.e.:

- choosing of zones most sensitive to changes of input parameters,
- optimisation of probe design.

It has to be noticed that to make possible monitoring of coal flames and fuel oil flames, which spectra are shown in Fig. 7 the spectral sensitivity of a detector should cover UV, VIS and IR range. This requirement is met by modified silicon detector which spectral response is shown in Fig. 8.

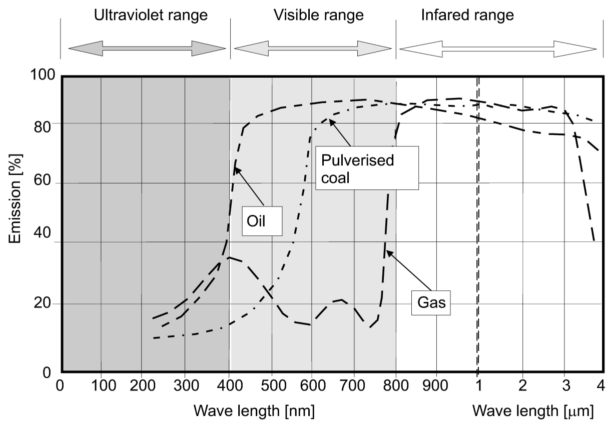

Fig. 7. Fuel-oil and pulverised coal flames spectra

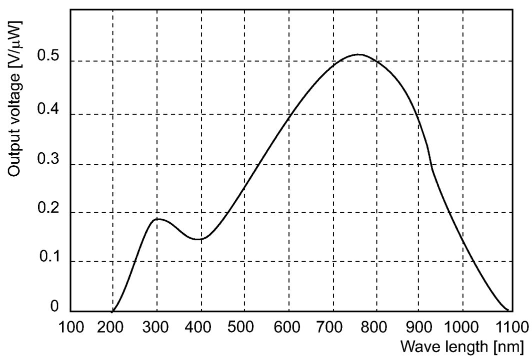

Fig. 8. Spectral response of the photodetector

The electronic part of the system allows measurement of flame luminosity variations with a frequency up to 10 kHz. Because the system mates an industrial control/measurement system operating at 1 Hz a full analysis of measurement data is done in its digital part and the system receives information in form of trends or bar-graph only.

Optimisation of probe design was made using multi-variant computer simulation with an aid of FLUENT programme implementing the finite elements method.

The probe made according to the results of simulation was tested on real object and operated free of maintenance during half of a year and was disassembled due to non-technical reasons. Assumptions were therefore met with a wide margin.

As it was mentioned a parallel research on determination of zone most sensitive to changes of input signals. Research was made at constant secondary air and variable primary air. Because quantitative measurement was not possible it has been decided to make qualitative measurements. It has to be understood in the following manner: for a given operation point of a boiler significant changes of secondary air are made maintaining the other parameters constant i.e. primary air and boiler load. These situations were conventionally named:

- high air (decreased amount of pulverised coal),
- normal air (amount of pulverised coal as for a normal operation of burner),
- low air (increased amount of pulverised coal).

Figure 9 shows example results of measurements of luminosity of each zone. In the initial phase slightly overlapping seven zones were chosen.

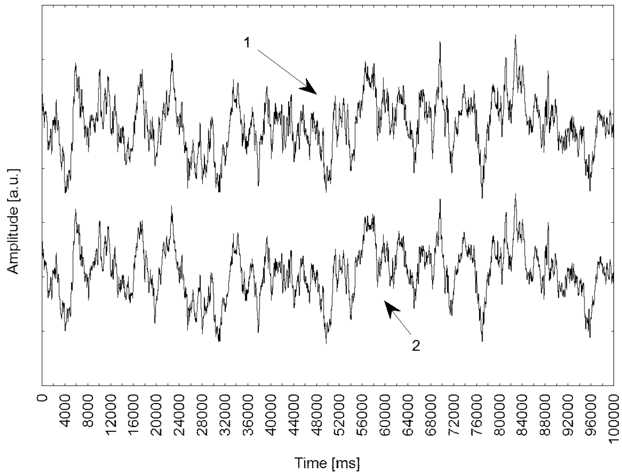

Fig. 9. Time series corresponding to the chosen flame zones

First conclusions which could be drawn on the basis of these experiments are as follows:

- second and third zones are the most sensible,
- first zone signal can be used as information about stability of the process.

4. Analysis of measurement signals

In the initial phase, the problem of formulating simple diagnostic criteria, which would be comprehensible and acceptable by the personnel was set. That's why measured flame signal analysis, that was proportional to temperature changes, allowed to determine range as well as it's changes velocity. The example results of this research are presented in the Fig. 10. It is notable, that they are very sensitive both to input signals parameters as well as type of fuel – Fig. 11.

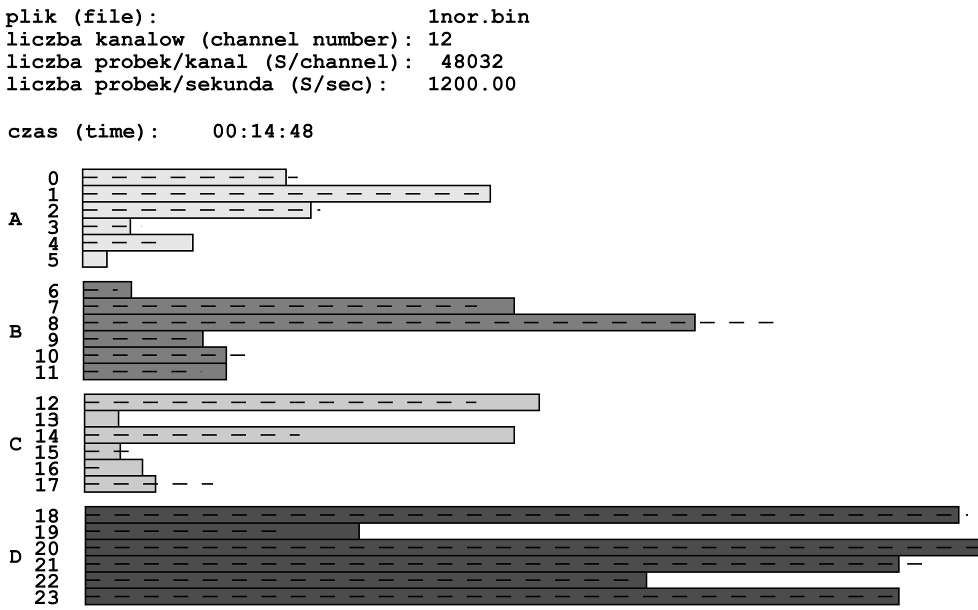

Fig. 10. Flame parameters corresponding to the specific flame zones (A – signal level, B – variable component of the signal, C – number of changes of the variable component around its mean, D – number of changes of derivative of the variable component around 0)

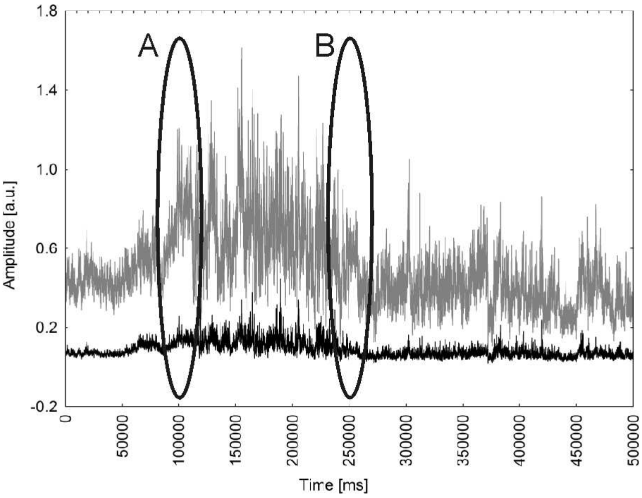

Fig. 11. Influence of type of fuel on flame signal level (A – fuel-oil switching on, B – fuel-oil switching off)

After initial research the hypothesis was established, that signal contains more information and ought to be appropriately analyzed. This contribute to achieve results for practical aims Fourier analysis, correlative analysis of the time series as well as wavelet analysis was used.

4.1. Fourier transform. The Fourier transform is one of the most popular method for signal analysis. Although, it can be treated as the mathematical functional, nevertheless, because of it's simple physical interpretation it has important practical impact. On one hand the Fourier transform belongs to the integrals transforms class. On the other hand, it does not include wide class of useful signals, such as finite power signals, periodic and almost periodic signals. The concept of the Fourier transform can be extended to Fourier transform in a boundary sense. This also provides frequency analysis of stationary stochastic signals [4–7].

Fourier transform for discrete signals. Numerical appliances of frequency analysis does not allow for access to the continuous signal $x(t)$, but only to it's samples $x(n)$ obtained via AD converter. Assuming that, signal $x(t)$ is sampled with appropriate frequency according to Shannon theorem (greater than double maximal signal frequency). The following equation can be written:

$$X(j\omega) = \int\limits_{-\infty}^{\infty} x_p(t) e^{-i\omega t} dt$$

$$= \int\limits_{-\infty}^{\infty} \left[x(t) \sum_{n=-\infty}^{\infty} \delta(t - n\Delta t) \right] e^{-i\omega t} dt \qquad , \qquad (1)$$

$$= \lim_{T\to\infty} \int\limits_{-\infty}^{\infty} \left[x(t) \lim_{N\to\infty} \sum_{n=\infty}^{\infty} \delta(t - n\Delta t) \right] e^{-i\omega t} dt$$

where $x_p(t)$ – signal samples.

Changing integration and summation sequence makes equation as follows:

$$\lim_{M\to\infty} \sum_{n=-N}^{N} \left[\lim_{T\to\infty} \int\limits_{-T}^{T} x(t)\delta(t - n\Delta t) e^{-i\omega t} dt \right] \qquad . \qquad (2)$$

$$= \sum_{n=-\infty}^{\infty} x(n\Delta t) e^{-i\omega \Delta t}$$

Practical appliances does not allow for summation with infinite ranges, that's why only fragment of the signal is transformed, i.e. N – samples signal length:

$$X_N(j\omega) = \sum_{n=0}^{N-1} x(n) e^{-i\omega \Delta t n} \qquad (3)$$

or represented as:

$$X(k) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) e^{-i \frac{2\pi}{N} kn}, \qquad (4)$$

$$k = 0, 1, 2, ..., N-1$$

named Discrete Fourier Transform (DFT).

Application of discrete Fourier transform. In order to determine the zone most sensitive to changes of parameters the measurements earlier described as qualitative were analyzed. Results for the most sensitive zones are shown in Fig. 12 to Fig. 15.

On the grounds of the above results it can be concluded that in all cases second and third zone are the most sensitive.

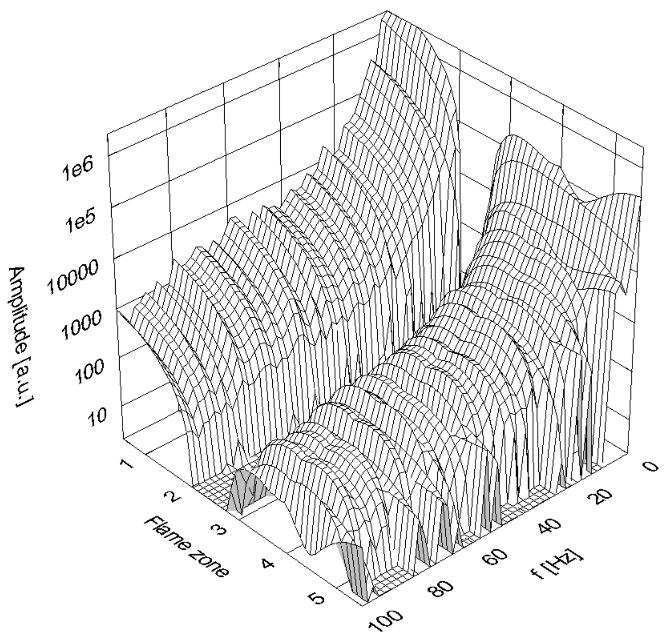

Fig. 12. Pulverised coal flame pulsation changes for the chosen flame zones (normal air)

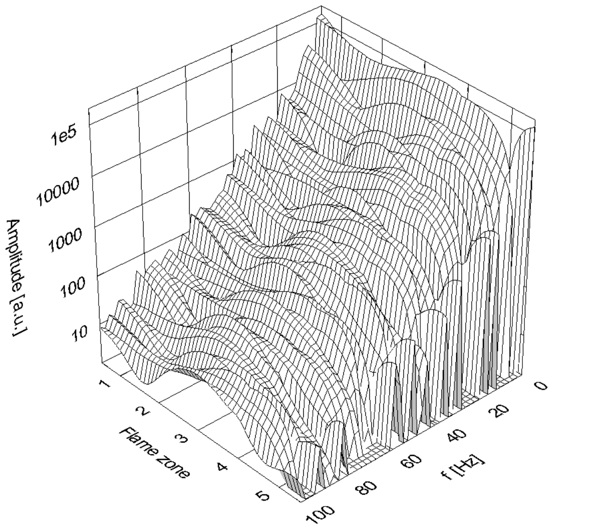

Fig. 13. Pulverised coal flame pulsation changes for the chosen flame zones (low air)

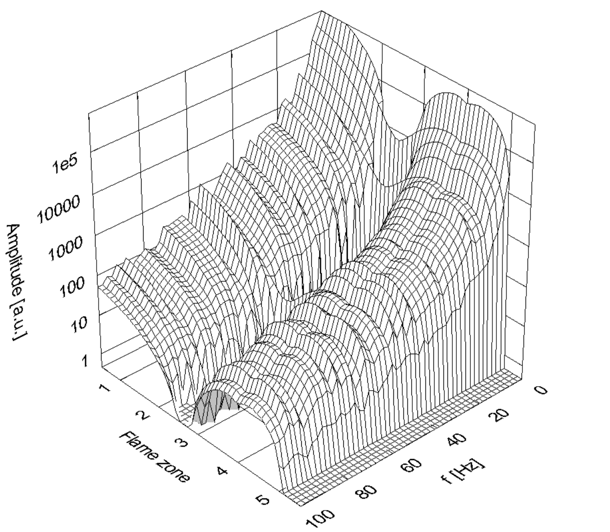

Fig. 14. Pulverised coal flame pulsation changes for the chosen flame zones (high air)

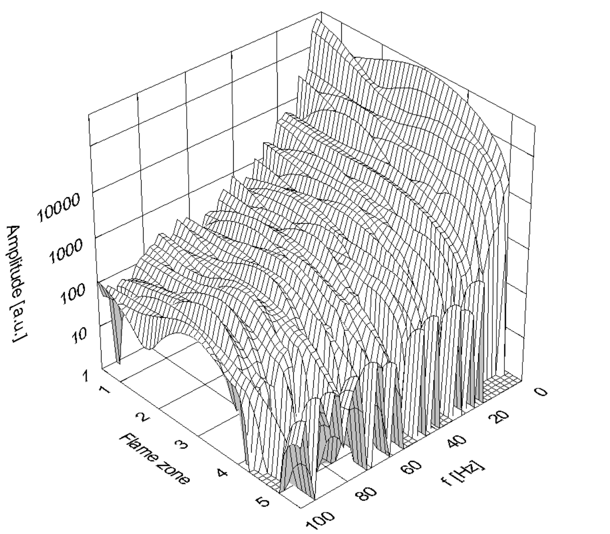

Fig. 15. Pulverised coal and fuel-oil flames pulsation changes for the chosen flame zones (normal air)

4.2. Time series analysis. Signals achieved during flame pulsation [8–10] may be treated as stochastic processes implementations and they may be featured as time-sequence observations that build up time series. Such kind time series, contained with N following observations may be treated as random sample of infinite samples population, generated by the given stochastic process. The superior aim of the analysis is achieving population property based on a trial. Their analysis can be lead through correlation structure research [11]. Nevertheless, for effective deduction, a formal description of the stochastic processes as well as time series should be implemented.

Stationary stochastic processes can be represented as:

a) ARMA (p, q) – mixed autoregressive processes, consisting of two parts, an autoregressive (AR) and a moving average (MA). The model is usually then referred to as the ARMA (p, q) model where p is the order of the autoregressive part and q is the order of the moving average:

$$\begin{aligned}\tilde{x}_t &= \varphi_1 \tilde{x}_{t-1} + \varphi_2 \tilde{x}_{t-2} + \ldots + \varphi_p \tilde{x}_{t-p} \\ &+ a_t - \Theta_1 a_{t-1} - \Theta_2 a_{t-2} - \ldots - \Theta_q a_{t-q}\end{aligned}, \tag{5}$$

where $\tilde{x}_t = x_t - m$ – mean deviance (where x_t – stationary), m – mean, φ_i – autoregressive part weights, $a_t, a_{t-1}, \ldots, a_{t-q}$ – random variable sequence with the mean = 0 and the constant variance: $E(a_t) = 0$, $E\left(a_t^2\right) = \sigma_a^2$, Θ_i – moving average part weights;

b) ARIMA (p, d, q) – autoregressive integrated moving average with (p, d, q) order. Despite of ARMA, this model is nonstationary and can be described with the equation:

$$\left.\begin{aligned} w_t &= \varphi_1 w_{t-1} + \varphi_2 w_{t-2} + \ldots + \varphi_p w_{t-p} \\ &\quad + a_t - \Theta_1 a_{t-1} - \Theta_2 a_{t-2} - \ldots - \Theta_q a_{t-q} \\ w_t &= \nabla^d \tilde{x}_t \end{aligned}\right\}, \tag{6}$$

where: $\varphi_1, \varphi_2, \ldots, \varphi_p, \Theta_1, \Theta_2, \ldots, \Theta_q$ – are model coefficients, ∇^d – d-time differential operator, w_t – diversified process.

It is notable that d-time differentiated process $\tilde{x}_t$, becomes a stationary process ARMA (p, q) type.

Real time series model identification. Time series is a sequence of data points, measured typically at successive times, spaced at (often uniform) time intervals. Basically, they are independent, and this relation character is relevant to sequence observation position. Finding structure of the stochastic process, that is generating time sequence, according to finite observation sequence stands the domain of the identification. Time series model identification may be divided to the following stages:

- primary identification,
- parameters estimation,
- considered model verification.

Primary identification and initial parameters estimation. The aim of the primary identification is to determine the model class. Autocorrelation is a mathematical tool used frequently in signal processing for this stage, as well as for initial parameters estimation. More precisely, for several stages qualitative (shape) as well as quantitative (value) features are used. To determine autocorrelation function following empirical moments (estimators) are used:

- mean value (m):

$$\hat{m} = \overline{x} = \frac{1}{N}\sum_{t=1}^{N} x_t, \tag{7}$$

where N – number of measures, x_i – individual measures,

- variance (σ_x^2)

$$\hat{\sigma}_x^2 = \frac{1}{N}\sum_{t=1}^{N}(x_t - \overline{x})^2, \tag{8}$$

- autocovariance (γ_k)

$$\hat{\gamma}_x = c_k = \frac{1}{N}\sum_{t=1}^{N-k}(x_t - \overline{x})(x_{t+k} - \overline{x}), \qquad k = 0, 1, \ldots, K, \tag{9}$$

- autocorrelation (ρ_k)

$$\hat{\rho}_k = \frac{c_k}{c_0}, \qquad k = 0, 1, \ldots, K. \tag{10}$$

Identification depends on subjective shape measure of the estimated correlation and partial correlation function, and their comparing with theoretical shape.

Initial parameters estimation is prosecuted with momentum method usage. The idea of this method is based on empirical moments usage as the estimators for appropriate moments of analysed distribution. Thus, moments are functions of distribution parameters, equations set are obtained as a result of such comparison. The solution of these equations is used for estimators of unknown model parameters. The estimators of moments of the considered stochastic processes are described by the equations numbered from (7) to (10). Replacing theoretical values by their estimates, the estimators for individual models can be solved. Precise algorithms of such approach are available in [12].

Parameter estimation and model verification. Estimators obtained by the momentum method may have poor asymptotic efficiency. Often they are used as primal approximation. To achieve effective parameters estimators, the highest reliability method have been used. Reliability function may be described by the equation [11]:

$$L(\varphi, \Theta, \tilde{x}_n) = \left(2\pi\sigma_a^2\right)^{-\frac{n}{2}} |M_n|^{-\frac{1}{2}} \exp\left\{-\frac{1}{2\sigma_a^2}\cdot\frac{S(\varphi,\Theta)}{\sigma_a^2}\right\}, \tag{11}$$

where $(M_n)^{-1}\sigma_a^2$ – covariance matrix $\tilde{x}_t$, $S(\varphi,\Theta) = \sum_{t=1-Q}^{n}[a_t]^2$, $[a_t]$ – conditional expected value.

Inquired parameters maximizes equation (11).

Obtaining model parameters, a new sequence can be investigated, and then compared with real sequence. The differences in appropriate time moments are used for model adequacy verification. It is the main reason for differences autocorrelation function $\hat{a}_k$ to be calculated.

Having appropriate model:

$$y = n\sum_{t=1}^{K} r_k^2(\hat{a}) \tag{12}$$

average distribution has $\chi^2(K-p-q)$, where n stands for the differences number $\hat{a}$. Using chi-square test χ^2, statistical hypothesis according to model adequacy may be verified.

Knowledge of time-series models allows to determine prediction of the future values. The most often, single step prediction are used because of extremely decreasing probability of the multi-step predictions. They play an important role in predictive control.

The exemplary results of the single step predictions obtained thanks to identification are presented in the Fig. 16.

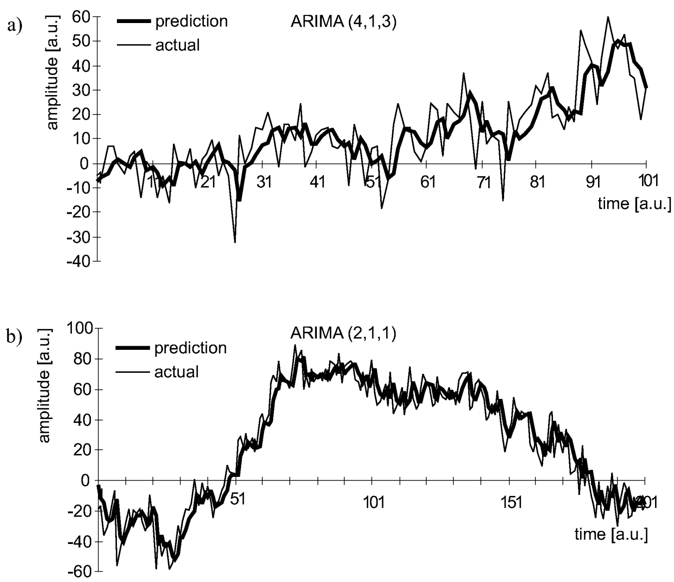

Fig. 16. The chosen measurements and single step predictions of flame flickering changes in power boiler

4.3. Wavelet analysis. Wavelet transform (WT) is a relatively new method of signal analysis, which does not have limitations characteristic for window Fourier transform. In case of short-time Fourier transform the window choice is arbitrary, what causes that dimensions of Heisenberg [13] box are constant. The wavelet transform uses a variable width window, which as a result of time domain translation, covers all the time instants. In consequence the time-scale signal representation of various resolutions is obtained. In case of wavelet transform the scale corresponds to frequency in Fourier transform. Wavelet transform, like Fourier transform, decomposes finite energy signal f(t) into a series of wavelet coefficients $\gamma(s,\tau)$ [14] which can be expressed (for continuous WT) as:

$$\gamma(s,\tau) = \int f(t)\psi^*_{s,\tau}(t)\,dt \tag{13}$$

where $\psi_{s,\tau}(t)$ is a set of base functions called wavelets, s, τ are scale and translation coefficients respectively and t denotes time.

Set of base functions $\psi_{s,\tau}(t)$ is obtained from a single prototype function by dilation and translation in time domain:

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right). \tag{14}$$

As opposed to Fourier transform, wavelet transform can represent a signal in time domain simultaneously at different resolutions. Moreover, the prototype function can be any function. However, it should have good localization in time (which means vanishing at $t \to \pm\infty$ and vanishing of its Fourier transform at $\omega \to \infty$ and $\omega \to 0$) and fulfil admissibility condition:

$$\int \frac{|\Psi(\omega)|^2}{\omega} d\omega < +\infty \tag{15}$$

where $\Psi(\omega)$ is a Fourier transform of $\psi_{s,\tau}(t)$. Some of wavelets are presented on Fig. 17.

As an example of application of continuous wavelet transform an analysis of signals of flame pulsation recorded during change of fuel being burned using Haar and Symmlet8 wavelets is shown. The aim of the analysis is determination of scales for which detection of fuel being burned would be most effective. It means determination which scales (frequency ranges) contain significant information about the change in fuel being burned. Results of analysis in form of scalograms are shown in Fig. 18 and 19.

An analysis of signal frequency structure variation which reflects changes in kind of fuel being burned is possible basing on continuous wavelet transform scalogram. Ignition of pulverised coal is accompanied by appearance of high frequency components, what is especially visible in case of wavelets well localizable in time domain (e.g. Haar). In the next instants a transitory amplitude increase tales place, which is the best reflected by wavelets with higher number of vanishing moments.

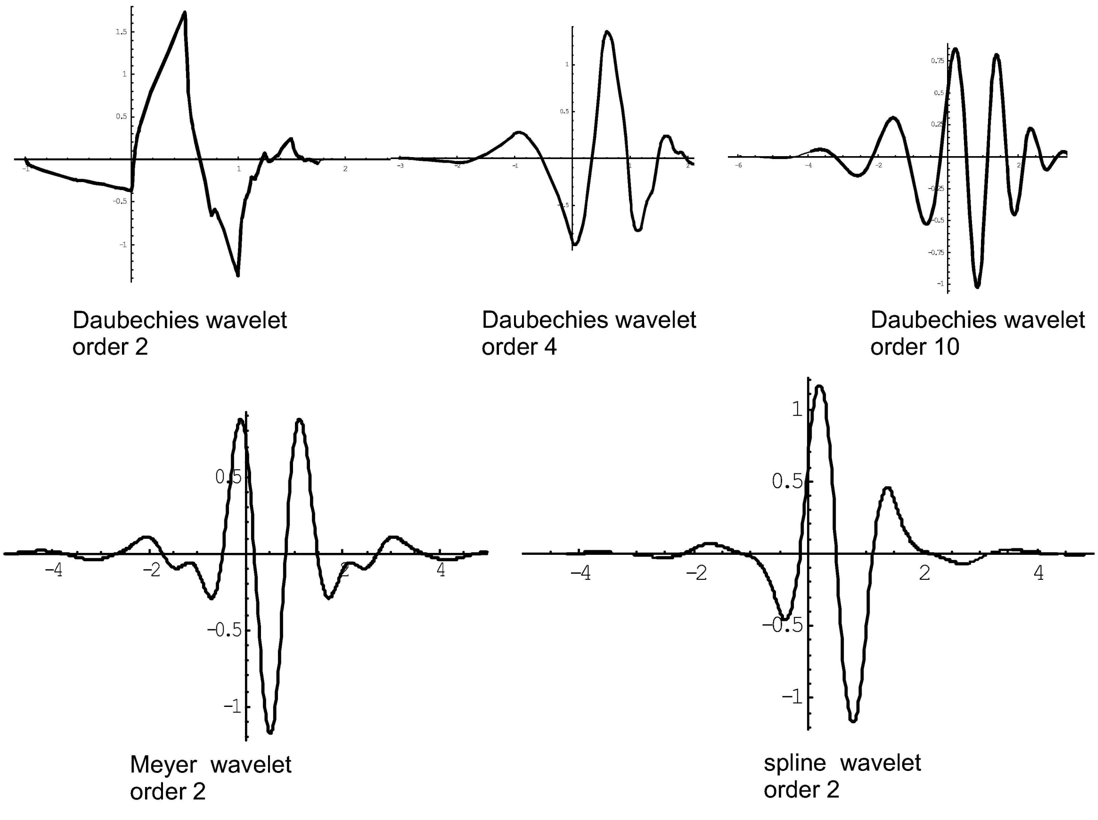

Fig. 17. Daubechies wavelets of 2^{nd}, 4^{th}, 10^{th}, Meyer and spline wavelets of 2^{nd} order

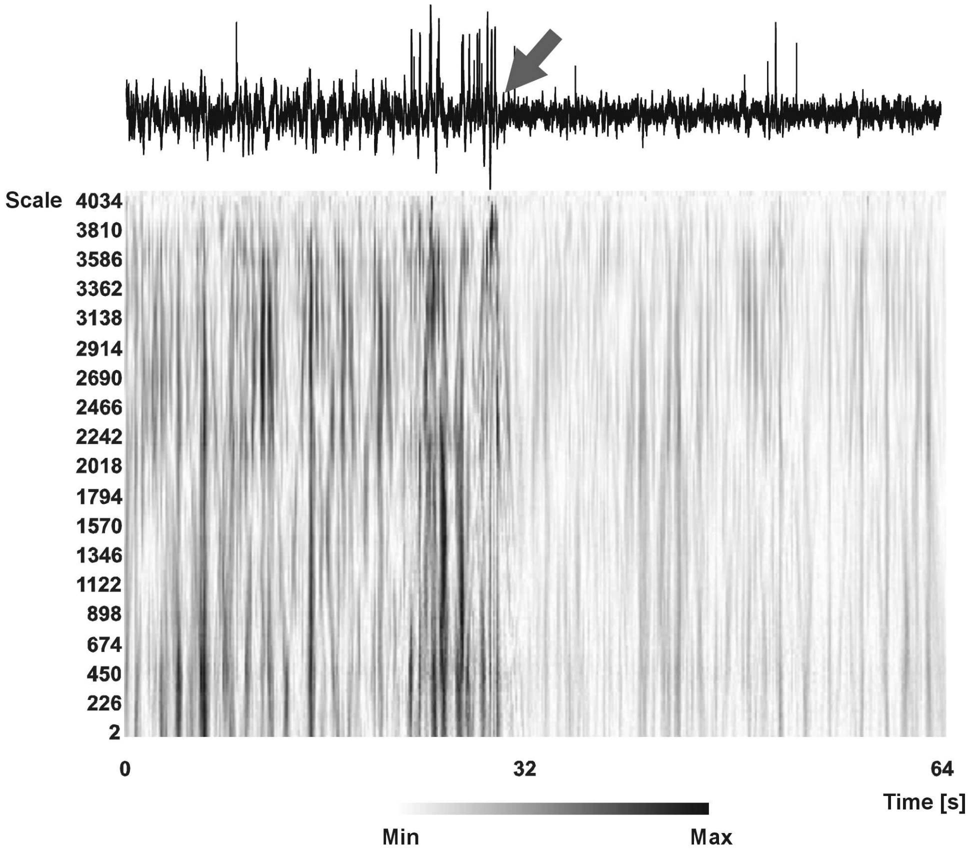

Fig. 18. Continuous wavelet transform scalogram (Haar) for signal representing fuel changer

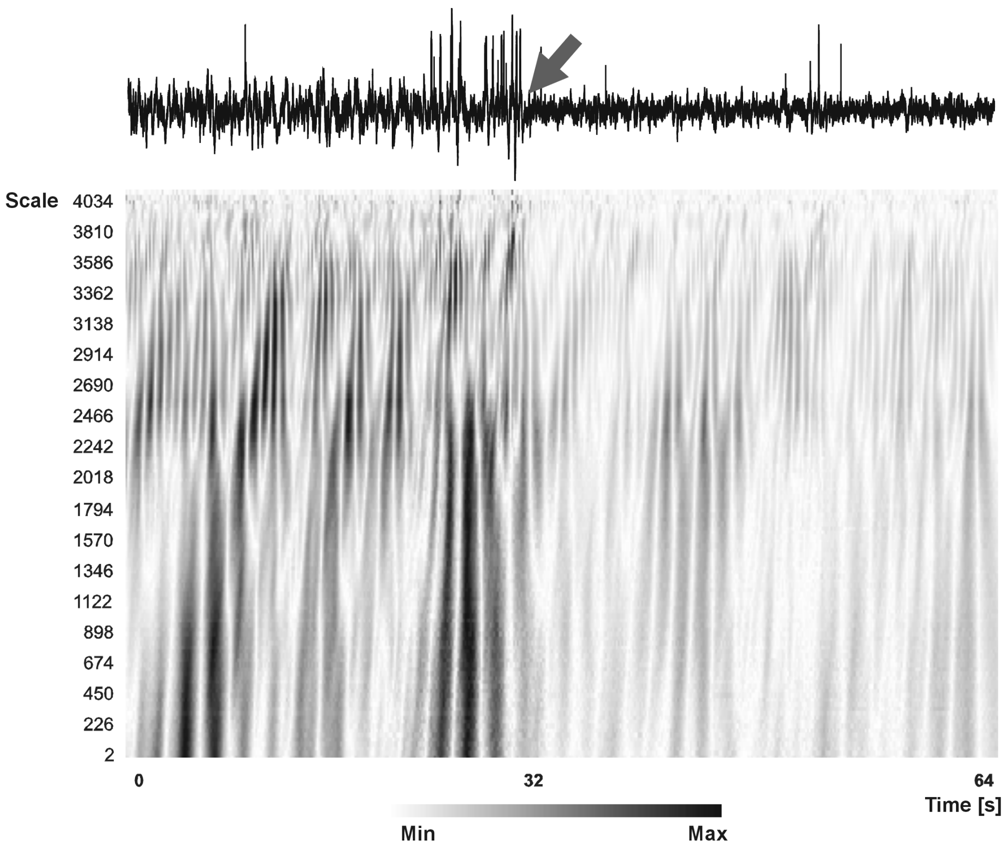

Fig. 19. Continuous wavelet transform scalogram (Symmlet8) for signal representing fuel change

Discrete wavelet transform. Practical realization of transform in meaning of (13), would be impossible due to continuity. Thus coefficients s and τ are digitized which leads to discrete wavelet transform (DWT). For the sake of computing optimization, it is convenient to set these coefficients as follows [14]:

$$s = 2^j, \qquad \tau = i, \tag{16}$$

where i, j are of integer, and to set the number of samples N to be equal to integer power of 2. This leads to $\log_2 N$ decomposition levels (Fig. 25).

The signal can be reconstructed through the inverse wavelet transform, which is (in the discrete case) sum of base functions weighted by corresponding wavelet coefficients:

$$f(t) = \sum_{j,i} \gamma(j,i)\, \psi_{j,i}(t) \tag{17}$$

where $\gamma(j,i)$ are wavelet coefficients series.

Signals of flame pulsation recorded during change of fuel being burned were analyzed using the discrete wavelet transform as well. Example results are shown in Fig. 20 and 21. Interpretation of scalogram properties is analogous to the analogue equivalents.

Using the discrete wavelet transform detection of the qualitative change of fuel is possible on the basis of signal transitional properties which variability character is similar to that of continuous wavelet transform.

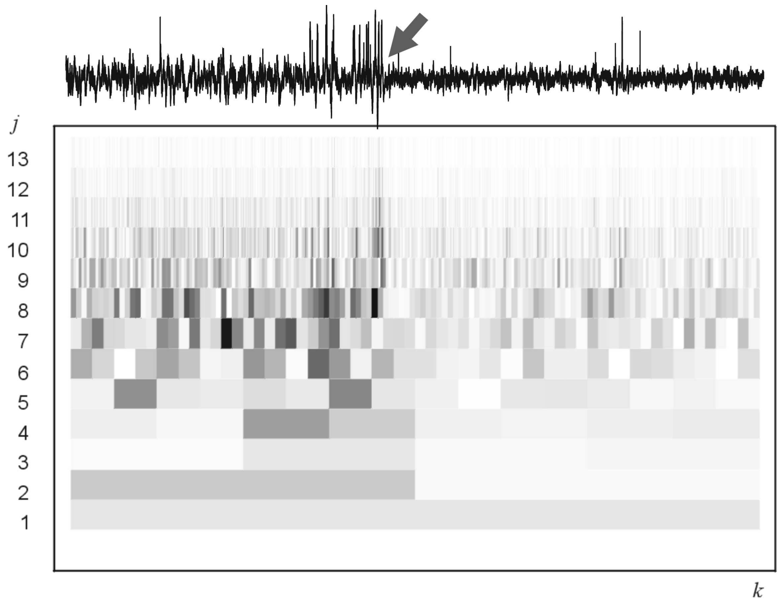

Fig. 20. Discrete wavelet transform scalogram (Haar) for signal corresponding to simultaneous combustion of pulverised coal and fuel oil

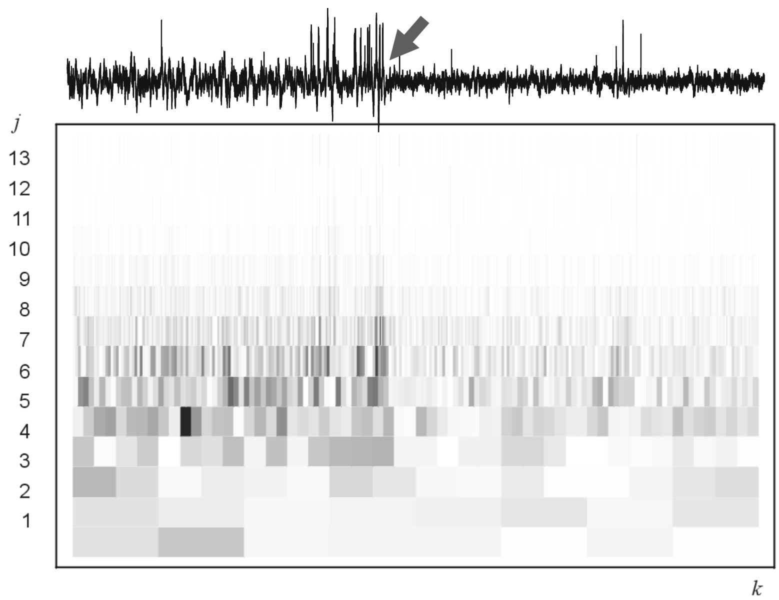

Fig. 21. Discrete wavelet transform scalogram (Daubechies8) for signal corresponding to simultaneous combustion of pulverised coal and fuel oil

Multiresolution analysis. A signal (or a function) $f(t)$ can be treated as composed of a smooth background and fluctuations or details on top of it. The distinction between the smooth part and the details is determined by the resolution, that is by the scale below which the details of a signal cannot be discerned. At a given resolution, a signal is approximated by ignoring all fluctuations below the scale. Increasing the resolution, finer details are added to the coarser description and finally the exact signal is recovered when resolution goes to infinity. So it can be written as:

$$f_{j+1}(t) = f_j(t) + d_j(t) \tag{18}$$

$$f(t) = f_j(t) + \sum_{k=j}^{\infty} d_k \tag{19}$$

where $f_j(t)$ is an approximation of $f(t)$ at a resolution level j and $d_k(t)$ are details at level j.

In the space of square-intregrable functions a multiresolution analysis is a nested sequence of subspaces $\{V_j\}$ ($j \in \Im$, where $\Im$ is a set of integers) such that [4]:

$$\ldots \subset V_{-1} \subset V_0 \subset V_1 \subset \ldots \subset L^2(\Re) \tag{20}$$

$$\bigcap_j V_j = \{0\}, \bigcup_j \overline{V_j} = L^2(\Re) \tag{21}$$

$$f(t) \in V_j \Leftrightarrow f(2t) \in V_{j+1} \tag{22}$$

$$f(t) \in V_0 \Rightarrow f(t-k) \in V_0 \tag{23}$$

a function $\phi(t)$, called the scaling function exists, such that $\{\phi(t-k)\}$ is an orthonormal basis of V_0.

Wavelet filtering of recorded signal. An example signal (Fig. 23) represents amplitude of flame flickering and is taken from single flame zone of single burner (Fig. 22). The signal, acquired with the speed of 1000 samples per second was recorded on OP-650 industrial boiler and represents sudden cut off of heavy fuel-oil (mazout) – pulverised coal is still present. Two fragments of equal length are taken form the example signal: A – pulverised coal with fuel-oil; signal B – pulverised coal (Fig. 23).

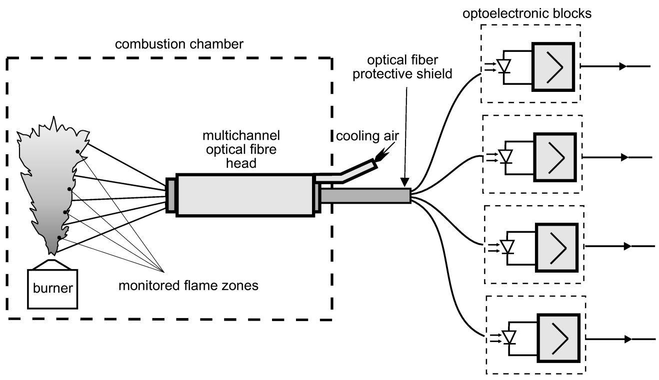

Fig. 22. Block diagram of the flame monitoring device

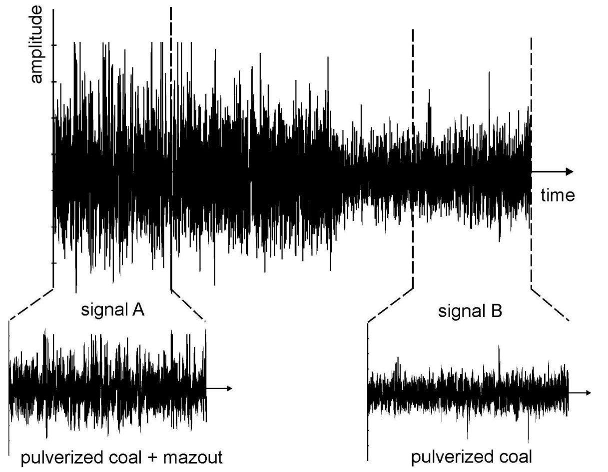

Fig. 23. An example signal recorded during starting up an industrial boiler OP-650 being analyzed

First stage of an analysis is removing constant component from each signal. Then, the signals are decomposed by discrete wavelet transform with appropriate filters. For each decomposition level (Fig. 25), the rms power was calculated in the case of both signals: $P_{A,l}$ (signal A), $P_{B,l}$ (signal B); l – denotes decomposition level. It can be achieved by setting all wavelet coefficients to zero, except the ones at decomposition level l and further reconstructing the signal through inverse discrete wavelet transform (Fig. 24).

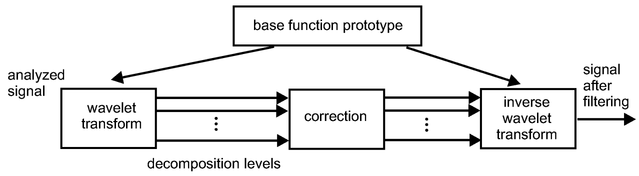

Fig. 24. Diagram of signal filtering

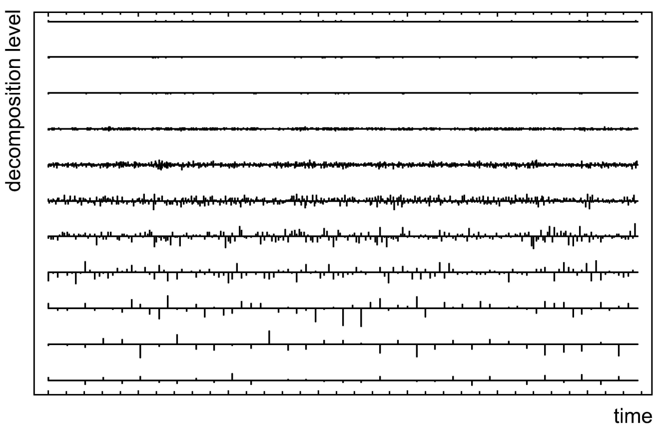

Fig. 25. Wavelet coefficients at decomposition levels for signal A

Calculations were done using as an example Daubechies, Coiflet Meyer and spline filter. In order to formulate the quality of filtering, a parameter k equal to quotient of $P_{A,l}$ and $P_{B,l}$ was introduced:

$$k = P_{A,l}/P_{B,l}. \tag{24}$$

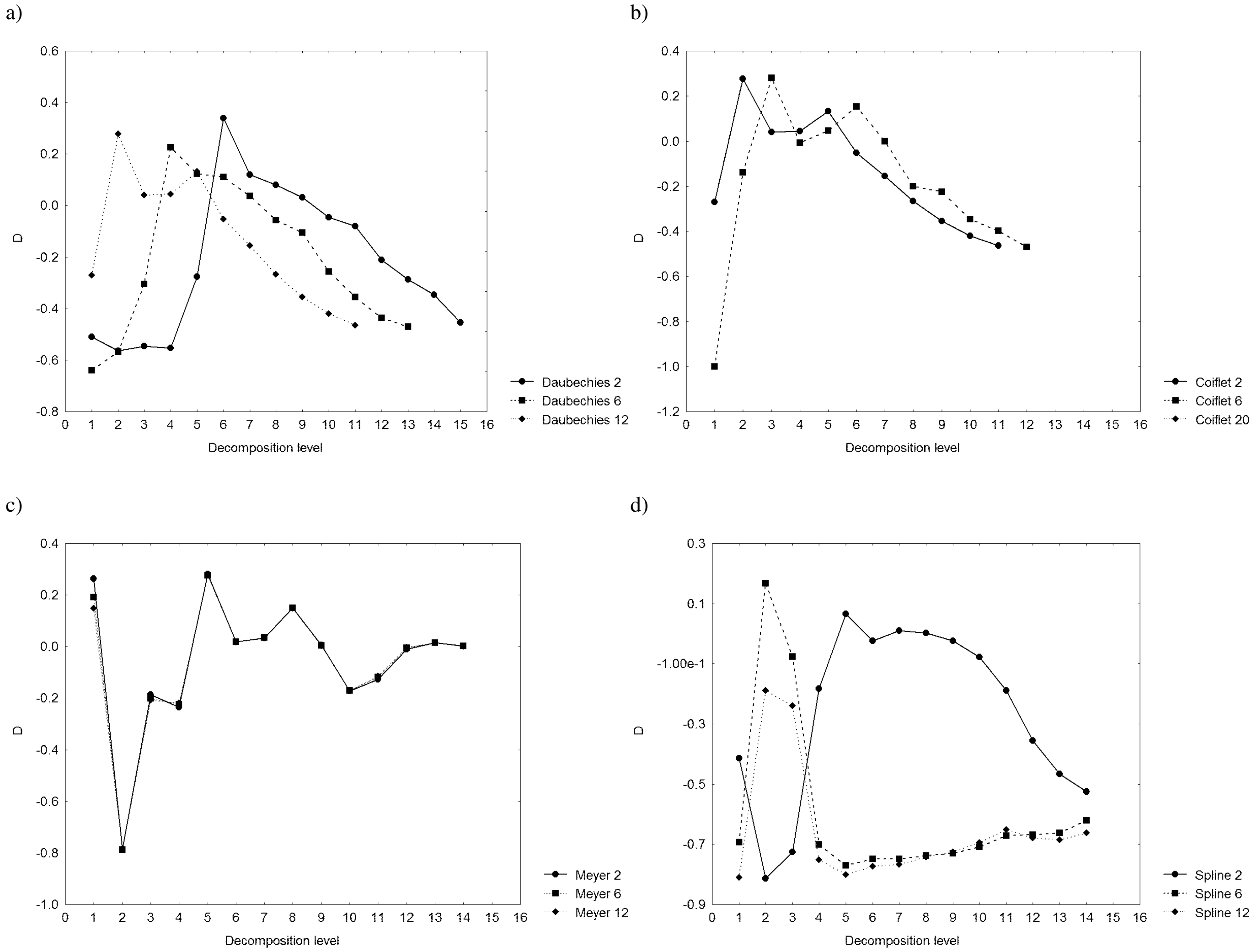

Fig. 26. Parameter D (14) for different wavelets at different decomposition levels

It was related to the equivalent parameter K, but computed for original (not transformed) signals:

$$K = P_A/P_B \tag{25}$$

$$D = (k - K)/K \tag{26}$$

where P_A, P_B is rms power of original signal A and B respectively.

If $D > 0$, it means that wavelet filtering enhances "distinguishing" between signal A and B. If $D = 0$, there's no use to apply such filtering.

The same procedure, but without the constant component removal, was carried out over the differentiated signals A and B.

The D parameter was computed for Daubechies, Coiflet Meyer and spline filter. The results are shown on Fig. 26 a-d.

5. Carbon monoxide measurements in the near-wall layer of a power boiler

One of the most dangerous consequences of application of low-emission combustion is considerable increase of corrosion of boiler elements. It is attributed especially to flame elongation and modification of distribution of fuel-air mixture in a flame. Other factor also influence a speed of a corrosion processes: coal composition, wall material, design of burners and boiler among others. Corrosion velocity increase causes shutdowns and repairs more frequent than usual. It is economically harmful, furthermore, the hazard of breakdown during operation increases, what may have unpredictable results.

Presently it is not possible to measure the corrosion rate continually or frequently enough to use these measurements to control a combustion process. Measurements of thickness of waterwall pipes are made only during the general overhaul of a power unit.

The knowledge of mechanisms that favour the corrosion allows development of methods of its monitoring and inhibition. Increase of reductive properties of layer of gasses that wash boiler's waterwalls are one of the parameters proving a progressing corrosion. These properties are strongly related with concentration of some gasses in the near-wall layer [15, 16]. Therefore, monitoring of composition of this layer may be used to estimate a corrosion rate and, what is more important, gas concentration measurements can be made continually without disturbing the medium.

Presently applied gas concentration measurement equipment is not suitable for near-wall layer gas composition. Power plants are usually fitted out with an equipment monitoring concentration of gasses beyond the combustion chamber. The conditions there are not as hard as inside the boiler what allows application of methods less resistant to a hard environment conditions. Furthermore concentrations of exhaust gasses differ considerably from the local ones inside a combustion chamber.

Near-wall layer flue gasses composition measurements carried out by various centres are based on sampling of gases from the medium under inspection. Unfortunately, it disturbs the medium being investigated and the response of such systems is delayed by process of sampling and sample conditioning.

The knowledge of concentration of chosen components of a gas mixture washing the power boiler combustion chamber elements of let us estimate their corrosion rate. It is possible to control the combustion process in such way that the nitrogen oxide emission is constrained to the required limits of NOx emission to the atmosphere simultaneously maintaining conditions that do not cause increased degradation of boiler's elements. For the sake of this a monitoring of medium inside a combustion chamber in the vicinity of waterwalls is necessary. It is about measurements of the so called high carbon monoxide concentrations (above 2%) [17] i.e. such that cause increased corrosion of boiler components.

Measurements of gas composition in the near-wall layer of power boilers suitable for process control may be done using optical methods. Adequate choice of optical path plays a significant role in obtaining sufficient measurement selectivity ad accuracy. It depends on expected concentration of a gas as well on spectral range used.

Up to now the exact dependence bonding concentration of carbon monoxide and corrosion rate has not been found. Research results lead to the following conclusions [15–17]:

- CO concentration below 0.2% means no low-emission corrosion,
- CO concentration around 0.2% is the conventional boundary of low-emission corrosion,
- CO concentration in the near-wall layer exceeding 3% supposes corrosion rate increase to more than 300 nm/h and exceeding 8% to more than 600 nm/h.

The observed dependencies allow utilization of information about CO concentration for corrosion rate estimation as well as for process optimization.

Selection of measurement method requires analysis of many factors such as possibility of disturbance (like vibration, optical system soil) influence on measurement result, the degree of overlapping of absorption spectra, expected mixture composition as well as price and availability of opto-electronic components. A measurement equipment cost and complexity are also important criteria of method selection.

Measurement of concentration of gases being product of combustion may be done using a series of methods [18]: Non Dispersive Infra Red – NDIR, Direct Absorption Spectroscopy – DAS, derivative spectroscopy, Differential Optical Absorption Spectroscopy – DOAS, wavelength-modulation spectroscopy – WMS and frequency-modulation spectroscopy – FMS, Fourier Transform Infra Red – FTIR as well as Gas Filter Correlation – GFC), laser correlation, or modified laser correlation.

Each one method assures good accuracy. Initial analysis let us conclude that carbon monoxide concentration measurement in near-wall layer gas mixture may be successfully done using lacer correlation method. It is characterised by simplicity of measurement system, acceptable sensitivity, low sensibility on wavelength independent losses, short response time.

Gas concentration measurement with the use of correlation method requires determination of absorption line profile for known conditions (concentration p_y, path length L_y) as a calibration measurement. The actual measurement consists in determination of absorption line profile for path length L_x and the partial pressure (which is a function of its concentration) is determined from [19]:

$$p_x = (1 - W_{MK})\, p_y \frac{L_y}{L_x}, \tag{27}$$

where W_{MK} coefficient is equal to:

$$W_{MK} = \frac{\int\limits_0^{\Theta_k} \left[h_y(\Theta) - h_x(\Theta)\right] \cdot h_y(\Theta)\, d\Theta}{\int\limits_0^{\Theta_k} \left[h_y(\Theta)\right]^2 d\Theta}, \tag{28}$$

furthermore:

$$h(\Theta) = \begin{cases} \ln \dfrac{I_0\left(\dfrac{\Theta_k}{2} - \Theta\right)}{I_1\left(\dfrac{\Theta_k}{2} - \Theta\right)} - \ln \dfrac{I_0(\Theta)}{I_1(\Theta)} & \text{for } 0 \le \Theta < \dfrac{\Theta_k}{2} \\ \ln \dfrac{I_0\left(\Theta_k - \left(\Theta - \dfrac{\Theta_k}{2}\right)\right)}{I_1\left(\Theta_k - \left(\Theta - \dfrac{\Theta_k}{2}\right)\right)} - \ln \dfrac{I_0(\Theta)}{I_1(\Theta)} & \text{for } \dfrac{\Theta_k}{2} \le \Theta \le \Theta_k \end{cases}, \tag{29}$$

I_0, I_1 is light intensity respectively before and after passing through the mixture, $\Theta = \lambda - \lambda_0$, $\Theta_k = \lambda_k - \lambda_0$, and λ_0, λ_k are beginning and end of light source tuning range and indexes y and x denote calibration and measurement respectively.

N_2, O_2, H_2O, CO_2, SO_2, CO are the most important gasses that may compose the near-wall layer. Their absorption spectra may overlap what may result in measurement ambiguity. It is therefore necessary to analyse such absorption line of considered gas which does not interfere with lines of other gasses. In the analysed mixture such line for car bon monoxide can be found within a spectral range between 1500 nm and 1600 nm. Within this range CO, CO_2, H_2O absorption may be observed as it is depicted in Fig. 27.

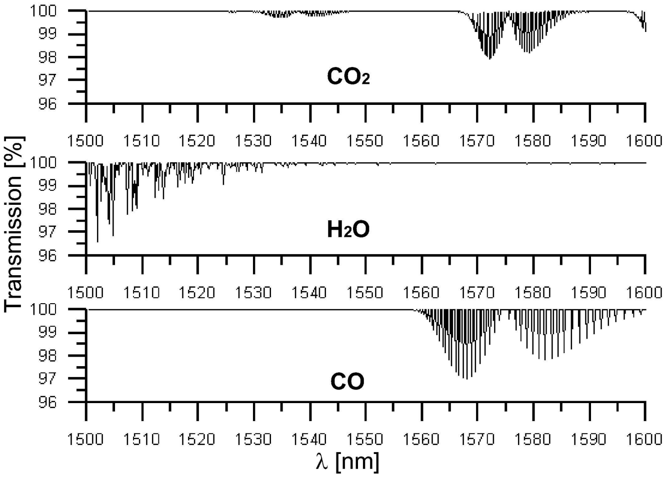

Fig. 27. Absorption spectrum of CO_2 (10%), H_2O (10%), CO (3%), path length – 10 m

The CO absorption line that meets the above condition and is relatively strong lies near 1566 nm. A device analysing this absorption line may be built using widely available optical (including optical fibres) and optoelectronic components.

Figure 28 shows example results of laboratory measurements of CO concentration in a gas mixture. The plot shows dependence between real and calculated values of products of partial pressure and optical path length. Measurement error does not exceed 10%.

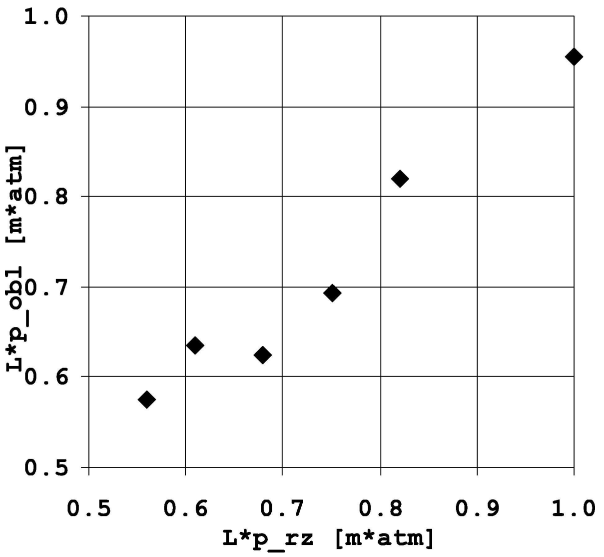

Fig. 28. Example results of measurements using laser correlation method (calibration measurement for partial pressure $p_{cal} = 1.00$ atm and $p_y L_y = 0.82$ atm·m)

Analyses made allow to conclude that utilization of laser correlation method allows determination of CO concentration in the mixture of near-wall layer gases. The method allows achieving a compromise between response speed and measurement accuracy. Because the measurement is being done inside the combustion chamber it is necessary to use high temperature optical fibres. Results of measurement obtained from such analyser may be used in advanced combustion process control systems.

6. Application of signals from the monitoring system to control an individual burner

6.1. Combustion process control system. The fuel-air subsystem is a part of unit power control system. It consists of two paths: the superordinated one for pulverised coal amount control and the subordinated air control path, as it is shown in Fig. 29. According to the power set by the Power Dispatch Centre the approximate amount of coal is calculated. Feeder rate of rotation and mill air flow calculated from mill load are the controlled values. The controller stabilizes an amount of oxygen in flue gasses. Amount of air fed to individual burners and OFA nozzles are controlled in the open loop. secondary to tertiary air ratio is set manually during the first run of the boiler and is not being changed between main maintenances [20].

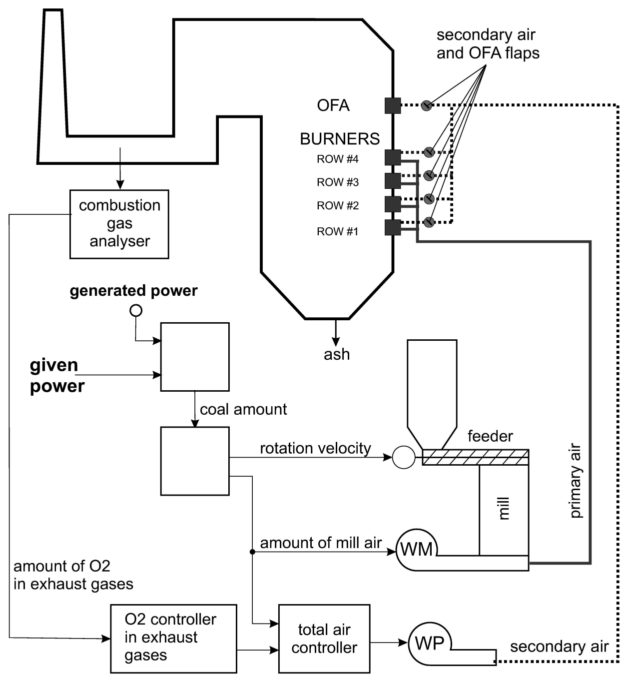

Fig. 29. Fuel-air subsystem control scheme

The most advanced of recently available controllers for pulverised coal burners allow closed-loop control of larger amount of parameters like separate air flows to individual burners and OFA, mill loads or additional amounts gasses like NOx, CO or SO_2 [20, 21].

6.2. Estimation of NOx and CO emission from individual burner. Because an individual air excess ratio rules an amount of NOx generated in a power boiler the closed-loop control of combustion process in individual burner would be the most beneficial. Nevertheless, there is a lack of method that would allow measurement of output parameters of an individual burner operating in an array like for example NOx or CO emission level. It induced to search a method which would allow at least estimating these parameters. Because the NOx level in flue gasses is the main criterion of pollution amount evaluation and CO level informs about combustion process efficiency, these gasses were chosen for further research. The fibre-optic combustion monitoring system developed in the Department of Electronics at Technical University of Lublin gives information about the quality of combustion. It also allows obtaining quantitative information. Because of strongly nonlinear dependencies as well as lack of an analytic model of a turbulent flame neural networks were used for estimation. Signals from zone of flame most sensitive to changes in air to fuel ratio were chosen for further analysis. A correlation between the optical signal and the chosen combustion process parameter was analysed. It is possible that further research proves a necessity to use signals from other zones of combustion. The signal was pre-processed in order to obtain two values:

- 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 according to the previous research the frequency spectrum of instantaneous changes of flame luminosity also contain information about combustion quality and it cannot be directly estimated by a neural network.

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. Therefore none of these values can be used individually.

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. The Lipshitz criterion for teaching series has been used for determination of the optimal order of model. It indicates that the lowest model error is expected considering 4 or 5 past inputs and zero outputs, what results in the simplest model Neural Network Finite Impulse Response (NNFIR). A higher order does not result in considerable error decrease but it may lead to an erroneous situation when external influence is considered as object dynamics.

Applied NNFIR(n_b, n_k) model has the following form [22]:

$$y(t) = g[\varphi(t), \theta] + e(t), \tag{30}$$

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 $\varphi(t)$ for NNFIR model has the following form:

$$\varphi(t) = [u(t - n_k), \ldots, u(t - n_b - n_k + 1)], \tag{31}$$

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

Such model was implemented as a multilayer perceptron with a structure MLP(10,4,1). According to the previous tests the best results have been obtained for this structure [23].

In case of emission of nitrogen oxides the model NNFIR(5,0) gave the best results. 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%. Figure 30 depicts NOx emission level plot recorded during one of experiments together with values obtained from the optical probe and the neural estimator. 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).

The 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. However even 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 Fig. 31 together with a plot of error with 10% boundaries marked.

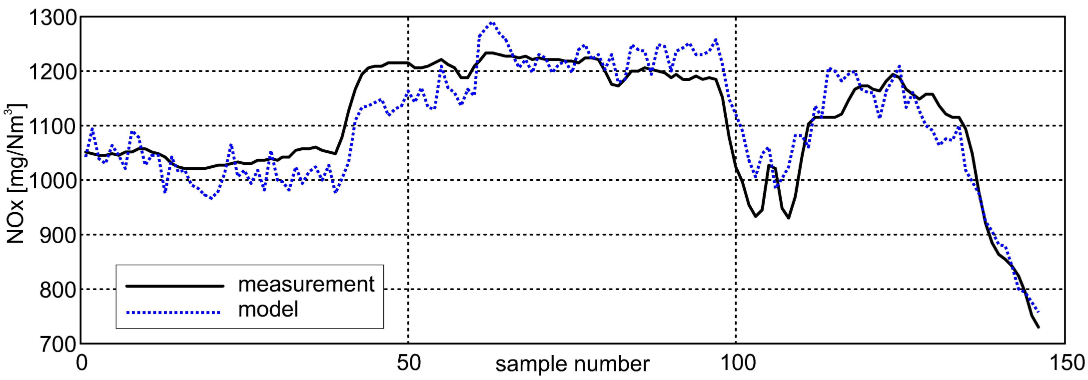

Fig. 30. Plots of NOx emission – measured (solid) and estimated on the basis of optical signals (dotted)

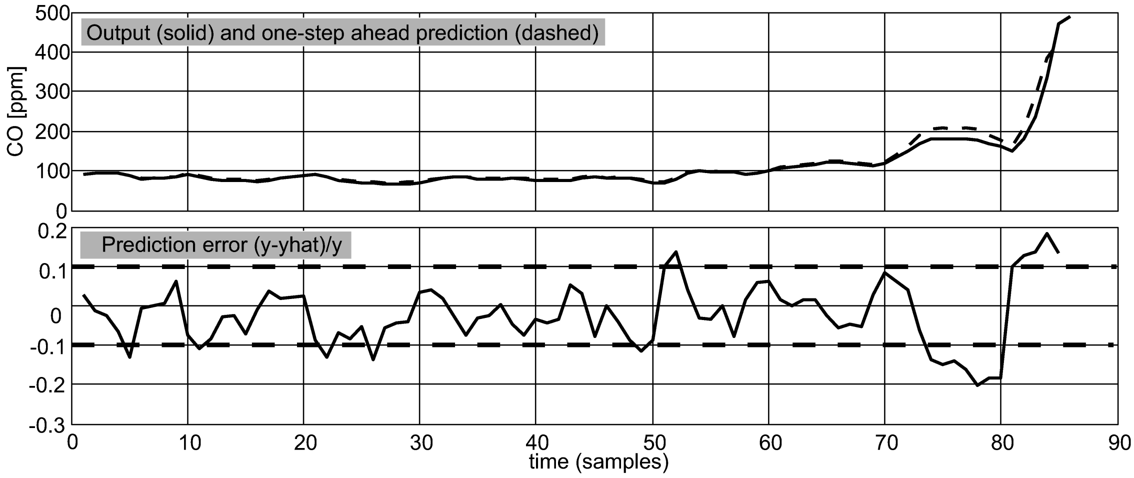

Fig. 31. Measured CO emission (solid) and estimated one (dashed) with marked error level

6.3. Control system. The idea of a controller stabilizing emission from an individual burner is depicted on Fig. 32. The information about amount of nitrogen oxides being emitted is obtained from the neural NOx emission estimator basing on the signals from the fibre optic flame monitoring system instead of from the gas analyser like in the presently utilized solutions. Analysis of the present control scheme indicates that the controller for the individual burner should operate in the inner control loop of secondary air, correcting settings of the superordinated system and the NOx emission set-point should be obtained from the optimization layer.

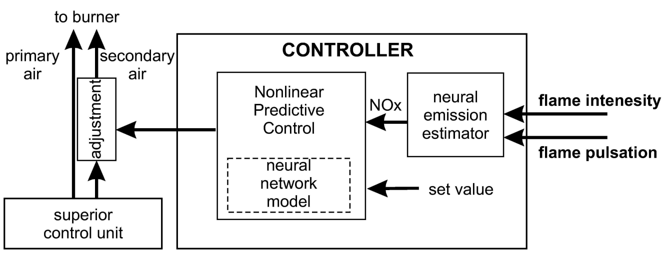

Fig. 32. Block diagram of the pulverised coal burner regulation

The quadratic control quality criterion of the following form was assumed:

$$J\left(t, U\left(t\right)\right) = \\ = \sum_{i=N_1}^{N_2} \left[r\left(t+i\right) - \hat{y}\left(t+i\right)\right]^2 + \rho \sum_{i=1}^{N_u} \left[\Delta u\left(t+i-1\right)\right]^2, \tag{32}$$

where $U(t)$ denotes the control vector, r is the reference, N_1 and N_2 are respectively minimum and maximum values of prediction horizon, N_u is the control horizon, $\hat{y}$ is the internal model output, ρ is the weighting factor and Δu denotes the change of control signal.

The criterion is minimized in the nonlinear prediction controller (NPC) with a neural internal model. An indirect control design was chosen because of simplicity of modification of the criterion, very useful at the stage of investigation.

The simulator of chosen parameters of a burner was constructed on the base of measurements. It was used for preliminary tests of the controller. Simulation research was related to ability to stabilize emission of nitrogen oxides.

Nonlinear predictive controller requires setting-up of three parameters: prediction horizon, control horizon and weighting factor (control variation to control error ratio damping factor). Because very small delay is expected the smallest initial prediction horizon value is assumed, i.e. $N_1 = 1$. The final prediction horizon value N_2 has been established experimentally. The remaining parameters were adjusted such to obtain a well-marked damping of control signal. In order to stabilize the system the final value of prediction horizon N_2 equal or greater than the internal model order is recommended [22]. In our case this value resulted too small. Stability was obtained for $N_2 = 11$.

In case of linear objects the prediction horizon value N_u is assumed to be greater than the number of instable or poorly damped poles. For nonlinear objects empirical adjustment is the only option. A long control horizon means large number of decision values in minimization of control quality indicator J resulting in longer computation. It is unjustified and in extreme cases may result in instability e.g. in case when the solution is not reached within the required period. Besides the output tends to oscillate the more the larger is N_u. Oscillations may be limited by increasing the weighting factor for control penalty ρ, nevertheless too high value results in prolonged settling-up.

Figure 33 shows plots of responses of the currently used control system, operating using a gas analyzer (dashed line) and the proposed one, operating on the basis of an optical signal (solid line). Both signals were synchronized in order to nullify a delay of gas analyzer.

As it can be seen using the adequate parameters for both controllers comparable setting time in the order of 20 sample periods may be obtained. Yet, the advantage of the proposed one is a possibility of closed-loop control of an individual burner as well as far shorter response time i.e. shorter time of output disturbance. It means lower amount of NOx emitted beyond limits. The response time of the proposed system (marked with "A") is always equal 2 sampling periods, while in case of the current one (marked with "B") depends mainly on measurement delay time. It can reach even several hundreds of seconds for big industrial boilers (case "C"). Of course if it would have been possible to measure emission from each individual burner with a gas analyzer. The use of fast analysers will be essential anyway.

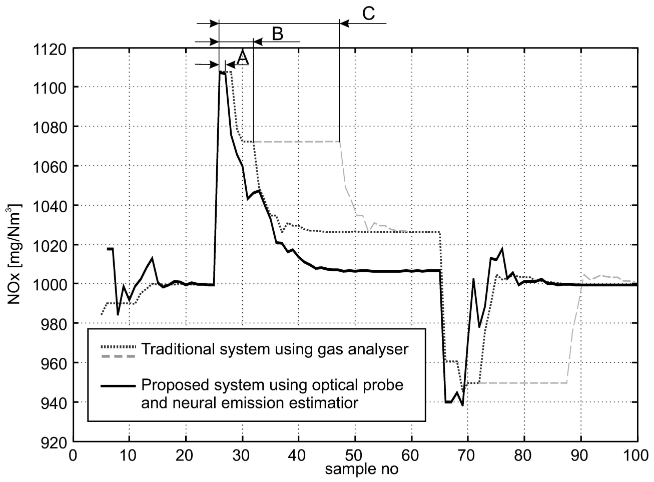

Fig. 33. Object response comparison for NPC obtained for various NOx emissions

7. Conclusions

The pulverised coal combustion process in power boilers analyzed in this work belongs to a class of complex technological processes. The magnitude and heavy conditions i.e. high temperature, dustiness, vibration and difficult access (special openings in waterwalls are needed to install optical probes, which can be made only by consent of Technical Supervision Authority) result in significant problems during industrial object research. The devices developed in the Department of Electronics, meeting the basic safety requirements for operation in such conditions, do not interfere the combustion process itself, allowed research which scope each time required consent and authorization of supervision authorities. Results of process monitoring were delivered to the control room as an additional information facilitating operation of the boiler. Deeper analysis of measured data with the use of contemporary analytical tools allowed diagnostics of combustion process in industrial conditions. Basing on obtained information a kind of fuel being burned may be distinguished, symptoms of deviation from the correct realization of the process may be indicated or overflow time and value of selected parameters may be determined. The research stimulated development of algorithm for control of individual burner which successful initial tests made in test facility in Institute of Power Engineering allowed to define directions of further research. Obtained results also allowed initiation of cooperation with Vattenfall Heat apart from the "Kozienice" Power Plant.

Further research will guide towards development of measuring devices allowing the real-time measurements of primary air fed to a burner and underburn as well as development of algorithms allowing control of individual burners in industrial power boilers with the use of the above mentioned measurements and planned ones. Such approach should allow meeting European Commission requirements regarding emission limitation of substances noxious for the natural environment.

REFERENCES

[1] W. Kordylewski, *Low-emission Combustion Technologies in Power Industry*, Wydawnictwo Politechniki Wrocławskiej, Wrocław, 2000, (in Polish).

[2] S.R. Turns, *An Introduction to Combustion, Concepts and Applications*, McGraw-Hill, Singapore, 1996.

[3] I. Glassman, *Combustion*, Academic Press Inc., London, 1987.

[4] C. Lou, H. Zhou, P. Yu, and Z. Jiang, "Measurements of the flame emissivity and radiative properties of particulate medium in pulverised-coal-fired boiler furnaces by image processing of visible radiation", *Proc. Combustion Institute* 31, 2771–2778 (2007).

[5] M. Taniguchi, K. Yamamoto, H. Kobayashi, and K. Kiyama, "A reduced NO_x reaction model for pulverised coal combustion under fuel-rich conditions", *Fuel* 81 (3), 363–371 (2002).

[6] W. Wójcik, "Flame pulsation measurements in industrial conditions", *Proc. V Scientific Conf. on Optoelectronics and Electronic Sensors* 2, 337–340 (1998), (in Polish).

[7] J. Szabatin, *Fundamentals of Signals' Theory*, WKŁ, Warszawa, 2000, (in Polish).

[8] W. Wójcik and A. Kotyra, "Zonal diagnostics of combustion process", *Proc. Conf. on Control and Automatization of a Combustion Process in Energetic Boilers*, 168–177 (2005), (in Polish).

[9] W. Wójcik, "Optical fibre system for combustion process monitoring", *PAK* 11 (53), 24–28 (2007), (in Polish).

[10] W. Wójcik, *New Directions of Energy Production and Use – Sustainable Energy Systems*, Lubelskie Towarzystwo Naukowe, Lublin, 2005, (in Polish).

[11] G.E.P. Box, G.M.Jenkins, and G.Reinsel, *Time Series Analysis: Forecasting & Control*, Prentice Hall, NewJersey, 1994.

[12] W. Wójcik, *Computer Stabilisation of Sludge Parameters in Cement Fabrication*, Doctoral Thesis, Lublin, 1985, (in Polish).

[13] T. Zieliński, *Digital Signal Processing. From Theory to Applications*, WKŁ, Warszawa, 2007, (in Polish).

[14] S. Mallat, *A Wavelet Tour of Signal Processing*, Academic Press, London, 1998.

[15] W. Bielikowski, "Corrosion of heated surfaces of boilers in low-emission combustion", *Elektroenergetyka* 03, 136(12)–144(20) (2001), (in Polish).

[16] H. Kruczek, "Usefulness of near wall layer for estimation of high-temperature corrosion hazard degree", *Energetics* 6, 419–427 (2002), (in Polish).

[17] J.N. Harb and E.E. Smith, "Fireside corrosion in PC-fired boilers", *Progress in Energy and Combustion Science* 16, 169–190 (1990).

[18] V.A. Firago, I.S. Manak, and W. Wójcik, *Gas mixture composition measurements using LD and LED absorption spec-*

troscopy, Akademia upravlenia pri Prezidientie Respubliki Bielarusi, Minsk, 2006, (in Ukrainian).

[19] W. Wójcik, P. Komada, S. Cięszczyk, V.A. Firago, and T. Golec, "Application of carbon monoxide optical concentration measurement for estimation of high-temperature corrosion rate", *PAK* 9, 311–313 (2005), (in Polish).

[20] W. Wójcik and A. Smolarz, "Stabilisation of NOx emission from an individual burner using NPC and neural method for estimation of combustion parameters", *PAK* 11 (53), 30–33 (2007), (in Polish).

[21] W. Wójcik and A.Smolarz, "Application of neural method of combustion parameters estimation for pulverised coal burner control", *PAK* 3, 30–33 (2005).

[22] M. Nørgaard, O. Ravn, N.K. Poulsen and L.K. Hansen, *Neural networks for Modelling and Control of Dynamic Systems*, Springer-Verlag, London, 2000.

[23] W. Wójcik, A. Kotyra, A. Smolarz, and P. Komada, "Optical fibre system for combustion quality analysis in power boilers", *Proc. Int. Conf. Optoelectronic Information Technologies* 4425, 181–187 (2000).