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Pulverized coal combustion boiler efficient control

Streszczenie. *Sterowanie procesem spalania jest zagadnieniem bardzo złożonym. Istniejące ograniczenia w tym zakresie wynikają z niepełnej wiedzy o nim, będącej konsekwencją niedostępności sygnałów pomiarowych procesu. Na podstawie badań przeprowadzonych na stanowisku spaleniowym zamodelowano algorytm sterowania MPC, pozwalający na efektywne sterowanie procesem z uwzględnieniem legislacyjnych ograniczeń emisji wolnych rodników. W artykule omówiono rezultaty badań symulacyjnych przygotowanych modeli i algorytmu sterowania MPC.*

Abstract. *Combustion process is very complex. Existing control restrictions comes out of the unavailability of certain signals and incomplete knowledge about the process. Combustion stand conducted research allowed to simulate effective MPC algorithm, that considered legislative emission limits of free radicals. The article discusses the results of simulation models and prepared MPC control. (**Efektywne sterowanie procesem spalania w kotle energetycznym**).*

Słowa kluczowe: kocioł energetyczny, proces spalania, układ sterowania, zaawansowane algorytmy sterowania.
Keywords: combustion boiler, combustion process, adaptive control system, advanced control algorithms.

Introduction

Combustion process is very complex, non-stationary and nonlinear and therefore modeling of industrial scale processes based on the theory of thermodynamics is difficult. Polish professional power industry faces the challenge of efficient management of the combustion process in plants, mostly derived more than 50 years ago. On the other hand it is notable that the concept of the efficiency of such a process should be understood not only in terms of technical and economic parameters, but also environmental. So the European Commission's submitted guidelines restricting the emission limit values (ELV) of NOx, CO and SO_2 in the atmosphere, instantly limited under the directives IIPC (Integrated Pollution Prevention and Control) and LCP (Large Combustion Plants).

In power generation, mainly based on the combustion of coal and biomass co-burning, much attention is drawn to the group of primary methods. It is estimated, that innovative technologies based on incremental methods will meet the rigors of ELVs , but with the half costs, comparing with the catalytic reduction methods.

To the significant environmental aspect, a counterweight stands the burden of the costs, difficulties and delays in obtaining permits in the context of new investments. Thus, an important issue in the face of this situation is a cheap reduction of nitrogen oxides (NO_x). Numerous publications, as well as conferences and symposia, raise problems of low-emission combustion technology.

The combustion process complexity, nonlinearity, occurring delays and disturbations as well as strict security issues, provides that, the most discussed and implemented solutions is based on mechanical modernization. According to literature, the basic methods available for low-emission combustion systems are limited to: reducing the combustion temperature, air distribution, fuel staging (reburning combustion and aerodynamics), and the usage of the reducing properties of the rich flame.

Systems combining various technologies and processes create favorable conditions, resulting in reduced NO_x, CO, and CO_2 emissions, mainly responsible for global warming. In order to reduce unwanted emissions there are also used modern technologies such as:

- high temperature incineration,
- oxy-combustion,
- heat recovery (heat and a cascade of low temperature heat utilization),
- catalytic combustion.

However, these methods are feasible almost exclusively in new, specially designed facilities and installations. The working facilities, existing improvements, uses advanced technologies associated with the use of a new generation of low emission burners and air grading schemes (OFA). An alternative, or complement solution to these technological improvements can be effective (optimized) combustion process control, which is the subject of this project.

As evidenced [1], intelligent control algorithms, used in the combustion process offer the great potential due to the significant complexity of the physical and chemical phenomena occurring in the considered process

The authors objective was to develop adaptive process control system of pulverized coal combustion and biomass energy in the boiler using information from both traditional measurements and additional information about the process.

Eco–control of pulverized coal combustion process

Opportunity to assess the quality of combustion is critical to proper operation of the boiler's energy [2]. In the case of combustion flow in layers, it translates to the speed of chemical reactions, heat transfer efficiency, flame stability and the generation of NO_x and CO. Literature [1-3] indicates that the greatest influence on the formation of combustion aerodynamics have the burners and the type of fuel and method of administration.

Low-emission burners use the reducing properties of enriched flame by the organization of understoichiometric combustion zones using air or fuel staging. It is notable that such approach in condition of dust excess conditions may deteriorate and increase the unburnt loss.

Taking into account these factors and the significant ecological aspects there is a need for such combustion process control system, that optimize boiler work, using information obtained from conventional instrumentation as well as incorporate innovative techniques.

One of the crucial parameters, from the technological point of view is to ensure flame stability and the detection/diagnosis of fault states. Thus, the control system should be completed with diagnostic information about the flame, using video technology or fiber-optic probes. Equally important are the quantitative information on concentration of nitrogen oxides (NO_x), carbon oxides (CO) and sulfur dioxide (SO_2) in order to provide normative constraints.

Rather difficult to define, but bringing valuable information about the process inputs would be continuous measurement of the pulverized coal amount/flow in the ducts/pipes. Similarly, but on the process outputs, it would be extremely valuable to obtain online information about the content of the combustible particles in the ash (especially organic carbon content).

Undoubtedly, obtaining such information requires a expensive test equipment usage. The associate problem is the method and instrumentation appropriate to such hard industrial conditions.

Imaging method in the combustion process

Radiation emitted by the flame is a reflection of the combustion process occurring in chemical reactions and physical processes. Optical diagnostic methods, in addition to acoustic [4-6] belongs to the most important methods, which allow the non-invasive way to obtain non delayed and spatially selective additional information about the ongoing combustion process. Regarding to the spectrum of flames in the visible emission, it is possible to include determine the content of the air-fuel ratio, the quantity of heat release and temperature [7-9].

Among optical methods, image processing based approach seems to be particularly important.

Flame still and apparent position stands the result of dynamic equilibrium between the local flame propagation speed and the speed of the incoming fuel mixture [10]. Changes of the flame front position in space, are seen as the flame shape fluctuations are disruption of this balance results. This allows to assume that the shape of a flame can be an indicator of the combustion process, occurring under certain conditions [11-13].

Mixed combustion tests of coal dust and biomass were carried out on the bench, whose main element is a cylindrical chamber with a length of 2.5 m and a diameter of approximately 0.7 m. Inside the chamber is made in the 1:10 scale model of dust swirl burner, along with the oil burner and gas ignition. The position is equipped with the facilities entrusted to the primary, secondary, and oil. Picture of flame from inside the combustion chamber was passed out through borescope equipped with a suitable cooling system. Borescope was installed at 45 degrees to the axis of the burner so that the analyzed image covered an area of the flame in the immediate vicinity of the burner (see Figure 1).

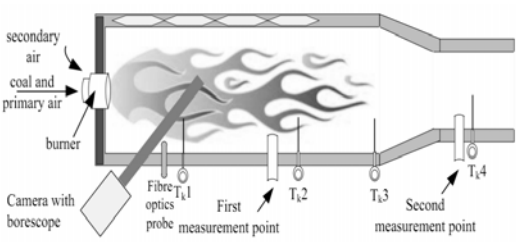

Fig.1. Responses NPC object NO_x emission to the control system regarding to different approaches

The combustion stoichiometric conditions were adjusted during the tests, by the secondary air flow adjustment. This resulted in fuel dust-air mixture changes exit velocity, bringing to the state of the close flame disappearance.

The area of the flame was isolated from the grayscale images, regarding to the amplitude of each pixel. It was assumed arbitrarily that the relevant pixel in the image belongs to the flame, if its amplitude is more or equal to the 64.

Evaluation of the simple geometric indicators based image analysis was determined in real time (50 images per second). The flame surface area was considered as the sum of all pixels belonging to the flame area and the length of the designated area contour.

Changes in these parameters are shown in Figure 2 (2a and 2b).

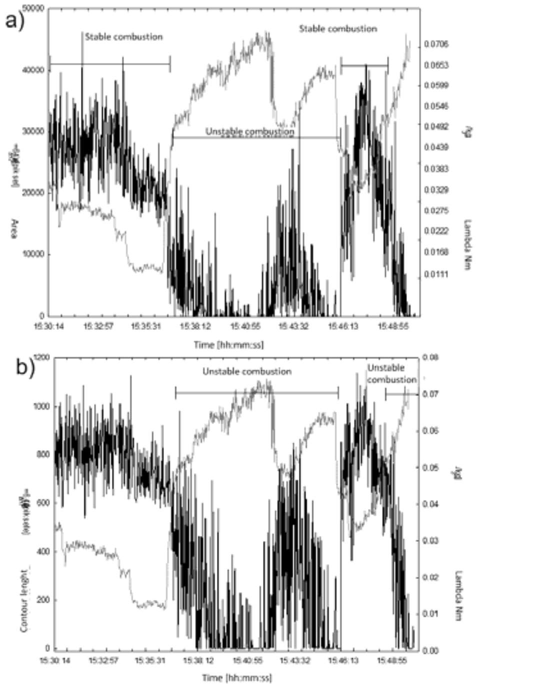

Fig. 2. Changes of the surface area of the flame (a) and contour length of the flame (b) for the stable and unstable combustion

In the first phase of the test, the combustion process proceeded stable, and the area fluctuated around the mean value. Reduction of air-fuel ratio results in a reduction of the average surface area of the flame. In the second phase of the test, increasing the secondary air flow causes the appearance of unstable combustion, the brightness of the flame decrease and intensive pulsations. This is accompanied by decrease in the average surface area of the flame (even to zero). The increase in air-fuel ratio is associated with a decrease in the flame contour length.

Optical methods and computational intelligence based combustion process diagnosis

The most popular method of reducing NO_x emissions by changing the organization of the combustion process, causes negative consequences for the operation of the boiler. The most important are: increased CO emissions, higher unburnt loss, the evaporator corrosion, increased slagging and instability of the flame.

These phenomena are undesirable or even dangerous to the boiler and it is less possible to achieve appropriate reduction of NO_x. This concludes needed for proper monitoring and control system. The most advanced automatic control systems for boilers firing pulverized work include closed-loop more parameters, such as separate air flow to individual burners and OFA nozzles, mill load, or additional signals from the exhaust gas analyzers such as NO_x, CO, and SO_2. However, because the excess air is an individual determines the amount of NO_x generated in the coal boiler energy [2, 14], would be most advantageous control of the combustion process in a single burner. However, there is no method that would allow the measurement of output parameters, such as emissions of nitrogen oxides and carbon monoxide, a single burner in the boiler running, or even an objective assessment of the quality of its work. This led the authors to seek a method that would allow at least estimation of these parameters. This involves the fiber optic flame monitoring system developed at the Department of Electronics Technical University of Lublin.

The first task was to develop a system for parametric evaluation of the quality of the burner pulverized. The content of nitrogen oxides was selected as the parameter in the exhaust, because it is important regarding to the quantities of pollutants emitted in general. Conducted correlation between the optical signal of the flame monitoring system and the selected parameter of the combustion flame zone was set. The analysis of the signal from this zone indicated two values: measure the intensity of the flame and measure the flame pulsation frequency. Then neural networks were used due to the highly nonlinear nature of dependency and lack of an analytical model to estimate the turbulent flame NO_x emission. Obtained neural model was used in simulations to estimate the parameters of the combustion control system for stabilizing emissions of nitrogen oxides from a single burner. Figure 3 shows the results of simulation - comparing the response to the control system operating on the basis of the signal from the gas analyzer (thin line) and based on signals from the optical probe (thick line). To allow comparison of the output signals are synchronized so as to eliminate the delay brought by the gas analyzer.

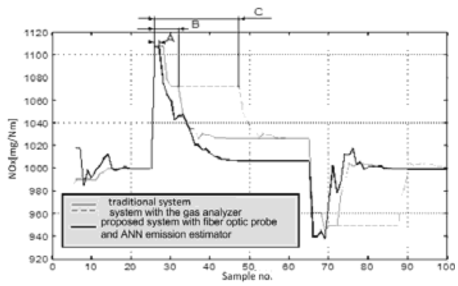

Fig.3. Responses NPC object NO_x emission to the control system regarding to different approaches

It is worth noting that, with appropriate values of controller parameters in the system with fiber-optic probe and the neural estimator emissions can be achieved by determining the response time of 20 sampling periods. This value is comparable to that achievable in the system with a gas analyzer. The advantages of the new solution are the single burner inclusion by the control loop and much faster system response to disturbance, or a shorter duration of the full value of the output noise (which means less pollution emitted). The delay time control system with an optical probe (indicated in the figure as "A") is not greater than 2 sampling periods, while in traditional solutions (indicated in the figure as "B") it depends mainly on the delay of the measuring system. In the case of large objects, such as power boilers in power plants, depending on the delay of the analyzers used can go up to several hundred seconds. In this case the gas analyzer system during the delay will not be able to detect the increased emissions. This mean very long duration of increased emissions. The time delay between the emergence of increased emissions and its detection by gas analyzers is marked with the letter "C" in the Figure 3.

The similar approach can be applied also in the case of combustion in gas turbines [15]. Laboratory tests performed for a gas burner showed that the optical estimator of the parameters of combustion in combination with the fuzzy controller exhibits good adaptability to changing working conditions and maintaining fuel NO_x and CO emissions below required levels, despite the considerable complexity of the task.

Research on using this approach to the variable fuel composition due to the trend of co-combustion with renewable fuels are promising. They show, that it is possible to estimate only the parameters of such combustion process by measuring the optical parameters of the flame, without knowledge about the combustion gases composition.

Proposed solution model

The model of the proposed control system of pulverized coal combustion process using information from two subsystems: a diagnostic and the video is presented in the Figure 4:

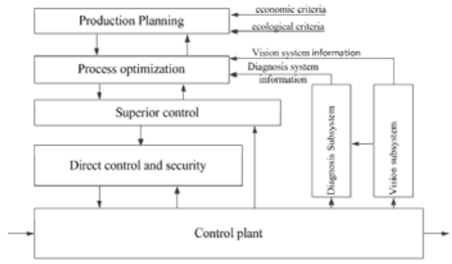

Fig.4. Proposed control system block diagram for the pulverized coal combustion

Master control system development with the control algorithm, that takes into account information from an image processing subsystem and the other diagnostic information requires the identification of the combustion process for a single low-emission burner.

In order to obtain the mathematical model of a single low-emission burner, the series of measurements were conducted on 0.5 MWth test stand in the Institute of Power Engineering in Warsaw. The experiments included the stabilization of the combustion chamber operating at different strengths, different types of fuel (coal and biomass taking into account) and a removable three types of low emission burners (with different angles of the blades).

Data were sampled with a resolution of every second. Belong to the registered size of multipoint measurements of exhaust gas concentrations (NO_x, O_2, CO, CO_2), measurements of temperatures, pressures and flows and levels drive the air fans.

The initial phase of work included analysis of selected, recorded input and output signals. For the purpose of the synthesis of multi-dimensional models (MIMO) set of input vectors, respectively quantitatively describe the flow of secondary air, fuel expense and vectors describing respectively the output signals NO_x, CO and exhaust temperature in the chamber, recorded in the first measurement point.

Data was divided into testing and validating sets. Then, the System Identification Toolbox package was used to identify the parameters for state space system, given with equation (1):

$$
\begin{aligned}
x(\mathrm{t}+\mathrm{Ts}) &= \mathbf{A}\,\mathrm{x(t)} + \mathbf{B}\,\mathrm{u(t)} + \mathbf{K}\,\mathrm{e(t)} \\
\mathrm{y(t)} &= \mathbf{C}\,\mathrm{x(t)} + \mathbf{D}\,\mathrm{u(t)} + \mathrm{e(t)}
\end{aligned} \tag{1}
$$

where: x – state vector, y – output vector, u – input (or control) vector, $\boldsymbol{A}$ – state matrix, $\boldsymbol{B}$ – input matrix, $\boldsymbol{C}$ – output matrix, $\boldsymbol{D}$ – feedthrough (or feedforward) matrix, $\boldsymbol{K}$ – gain matrix [5].

The achieved models were conducted for the three specified points of work (three power values, the stabilization of temperatures, homogeneous fuel). Selection of the model order was empirical. In most cases, it accepted the value from the interval <3, 11>. Results of matches (in terms of MSE, expressed in percentage) is given in Table 1.

Tested, complex object was treated as a serial structure system. It means that the outputs of the first level models provide inputs for models of second-level (as defined in

Table 1 as Models 2) and describe the relationship between the concentrations of NO_x, CO, flue gas temperature in the chamber and the analogous values in the corresponding measurement point.

For further analysis of selected models at 60% match in terms of MSE.

Table 1. Model fit results for the first and the second identification stage

	Models 1					
	P1		P2		P3	
Test set	D1M1_4s11	D1M1_4s6	D2M1_4s6	D2M1_4s5	D3M1_4s3	D3M1_4s4
D1	**64,77**	**59,89**	58,51	57,98	56,92	58,65
D2	47,28	57,48	**60,25**	**59,42**	55,51	56,49
D3	62,65	64,84	63,41	64,12	**66,81**	**70,25**
	Models 2					
	P1		P2		P3	
Test set	D1M2_4s10	D1M2_4s3	D2M2_4s4	D2M2_4s10	D3M2_4s10	D3M2_4s6
D1	**64,58**	**62,62**	61,67	59,77	54,33	54,96
D2	67,23	66,22	**71,14**	**73,33**	59,12	58,65
D3	53,06	55,39	53,74	53,14	**54,47**	**52,35**

Combustion burner models validation

To verify the reliability of the obtained models, the Matlab/Simulink environment was used. Designed MPC controller allowed to impose boundaries to the outputs and controls, disturbance signals and also determine the prediction and control horizons [16, 17]. Therefore it also offers the possibility to verify models in the context of normative constraints (eg, the NO_x emissions).

The tests carried out, taking into account restrictions on NO_x emissions standards (300 ppm), best results were obtained for models of low-emission burner first (D1M1_4s6) and third (D3M1_4s3). In the case of P2 models meet emission reductions were achieved with the occurring oscillations (D2M1_4s5) and case (D2M1_4s6) - failed. Serial configuration has brought the best results in combination structure models (D2M2_4s4 and D2M2_4s10).

Conclusion

Radicals (NO_x, CO and SO_2) emission requirements are becoming more restrictive. Therefore, there is the emerging need for optimum control of combustion using low-carbon technologies. The paper discusses the conditions for the development of the combustion process control system and create an algorithm to optimize the boiler operation based on information obtained from conventional instrumentation and incorporate innovative techniques to assess the quality of the process.

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