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Neural Network Evaluation of Combustion Process for Continuous Control of Small Scale Biomass Fired Boilers

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Abstract: Boilers based on combustion of biomass become widely used as a heating source nowadays. The modern ones are typically controlled automatically. The control algorithm of those boilers is crucial in reaching optimal operational conditions by means of maximal efficiency and minimal environmental impact. On the other hand, the acquisition costs of these advanced devices should be maintained at reasonable level. This paper deals with implementation of modern proper control algorithm and obtaining the necessary input values that cannot be easily measured operationally by a direct measurement.

1. INTRODUCTION

Biomass combustion is used very long time for the heating of houses and residences in a world, especially because of its availability. Its advantage over e.g. coal is its CO_2 neutrality because the CO_2 emitted to the atmosphere was taken from it during the biomass cycle growing, i.e. no new CO_2 is added to the atmosphere from the underground (van Loo *et al.* 2008, Lackner *et al.*, 2010). The combustion devices have been traditionally operated manually; the efficiency of combustion then has depended on the skills and experience of device operator. To increase the efficiency of combustion globally, it is necessary to introduce advanced control algorithms to these devices. The improvement the efficiency of combustion by improving the construction is already close to the limits (Yin *et al.*, 2008, Korpela *et al.*, 2008, Plaček *et al.*, 2011).

Nowadays, the algorithms used in automatic biomass fired boilers are typically automated variants of how the operator would operate the boiler manually. They are based on simple on/off control almost exclusively when the small-scale boiler are controlled. However, the on/off control can cause process variables transitions that increase emission of harmful flue gasses and decrease the combustion efficiency. So, there is a try to replace these heuristic algorithms by the modern algorithms based on control theory (Korpela *et al.*, 2009).

On the other hand, the full-scale boilers went through expensive development that has lead to use of expensive instrumentation. The cost of instrumentation is a main factor that limits significantly the use of full-scale boilers control algorithms to small-scale ones (Lackner *et al.*, 2010). There are also several approaches to model their behaviour (Neuman *et al.*, 1999, Neuman *et al.*, 2000). However, there are also other factors that make the use of full-scale boiler control approach to control small-scale boilers problematic:

- small-scale boilers are usually operated by operators with low experience and usually they neglect the maintenance,

- the low-priced sensors provide inaccurate process variable values, the use of fuel which has low quality and unguaranteed consistency, etc.

The transfer of full-scale boiler control algorithms to the small-scale ones is made more difficult by different dynamics that is significantly faster in small-scale boilers a by higher sensitivity to disturbances (Haapa-aho *et al.*, 2011, Oswald *et al.*, 2012).

The goal of work presented in this paper is to improve boiler behaviour without the necessity to modify the boiler construction and significantly extend the instrumentation, as both (and especially the second one) can lead to the increase of the manufacturing costs. The work goes through three different, however cooperating fields: replacement of on/off control algorithm with a continuous controller, development of an optimizing algorithm to properly set the parameters of the used controller, and evaluation unmeasured parameters on the basis of operationally measured process variables.

2. EXPERIMENTAL EQUIPMENT

The experimental consists of two boilers of different nominal heat power. The small-scale one is of heat power 25 kW, the midscale is of heat power 100 kW. Both boilers are controlled with Programmable Automation Controller (PAC) WinPAC line 8000. This PAC type has been chosen because it producer ICP DAS base it on open architecture, and then it is well documented. The PAC is based on processor ARM and powered by Windows CE. Then, it is possible to develop

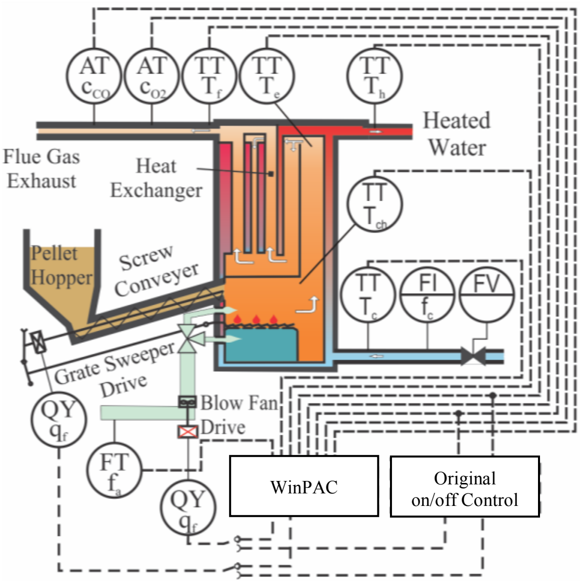

Fig. 1. Scheme of the used small-scale experimental boiler

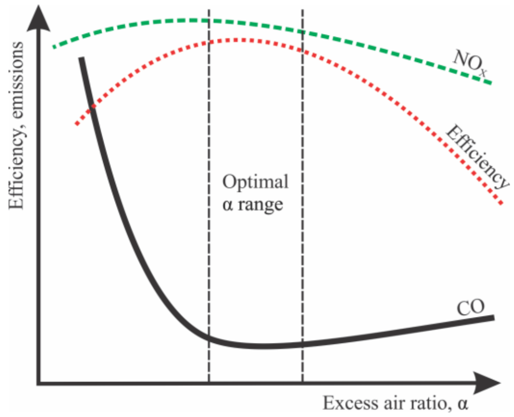

Fig. 2. A dependency of CO and NO$_x$ production and efficiency on the amount of exceeding air

own control algorithm on various level of sophistication directly on the lowest software level or to use already developed control software. We have chosen to use the control software REX from University of West Bohemia in Pilsen. The REX control software is compatible with Matlab/Simulink; the algorithms can then be developed in Simulink and after compilation they can be downloaded to PAC for real time execution. The REX control software moreover allows powerful communication between REX and Simulink via Ethernet, which can be used to monitor the experiment in real time and remotely. The communication between two PAC with REX control software, which potentially opens a way to experiment with even more sophisticated control algorithms allowing more boilers to cooperate or adapt the operational regime of respective boilers in dependence on regime of other boilers.

The small-scale experimental boiler is based on commonly marketed boiler Verner A25G, where its hardwired control unit was replaced by WinPAC mentioned above. For experimental purposes, its instrumentation has been extended by some items for better understanding of combustion process and it is not intended to present in commercially marketed version of boiler. The frequency changer has been added to control inlet air fan to allow its continuous control. Three thermocouples have been added to obtain more information about temperature courses. The emission analysis unit has been connected to obtain the information about the dependency of emission structure on the operational regime of the boiler and it correlation to other variables. However, we had to respect the request to remain the possibility to disconnect the new control unit and connect the original hardwired control electronics. The principal scheme of the boiler with extended instrumentation is in Figure 1.

The medium-scale boiler has been built with different approach. It is unique experimental device with specially constructed grate, but equipped with common PLC Siemens based commercial electronic, which is a standard component of boilers Fiedler. In this case, WinPAC does not replace the standard control electronic, but cooperates with it. This allows comparison of results when the boiler is controlled by

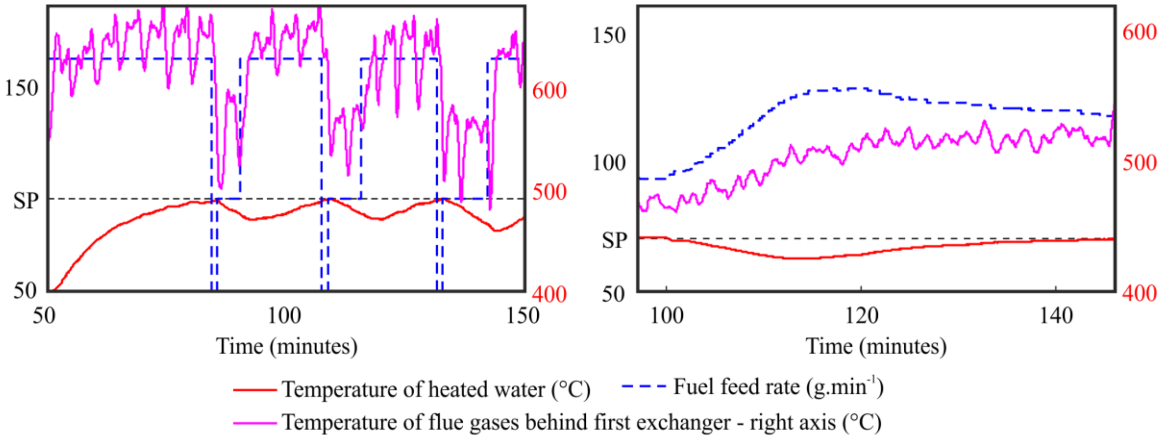

Fig. 3. Comparison of heated water temperature variance and volume of emissions when fuel feeding is controlled by original fuel feeding algorithm (on the left side) and PI controlled feeding (on the right side)

the commercial control algorithm and newly developed control algorithm. In a regime of PLC Siemens control, WinPAC can monitor its operation, in a regime of WinPAC control, the PLC Siemens operates as input/output modules of WinPAC. This combination of WinPAC and PLC Siemens also allowed us to decrease the costs of experimental equipment, because it is not necessary to equip WinPAC with all the I/O modules that would be needed in a case when PLC Siemens would not be present. The standard instrumentation is then connected to PLC Siemens; the extended instrumentation is connected directly to WinPAC. The communication between WinPAC and PLC Siemens is done via MODBus.

3. PROPOSED CONTROL ALGORITHM

The main goal, which resulted from previously conducted experiments and from discussions with the boiler manufacturers, is improving the approach how the heat output is controlled. Originally, the on/off control was used so that when the temperature of heated water increased above the set point, the fuel feeding and when its temperature decreased, the fuel feeding was restored is steps. The control was inefficient as many transients occurred during operation, during which the combustion process fluctuated and significant amount of unburned fuel flowed out as a part of flue gasses. To prevent this, we replaced the on/off control algorithm by PI controller that maintains the combustion more stable and then emitting lower amount harmful gasses. The simple model of boiler in a form linear differential equation has been created and the method of Dynamic Compensation was used for setting the proper PI controller parameters. The fluctuation has been eliminated (see Figure 3) and, more over, the boiler got the ability to operate in a range of 60 to 100 % of nominal power without significant loose of efficiency. This was not possible with original control algorithm; the original algorithm caused significant losses when the boiler was operated on lower heating power than nominal.

However, the parameters of the obtained model depends on many often invaluable properties and differs with different boiler construction, used fuel, air humidity, and many others, we need to develop the controller adaptation mechanism based on generally valid formulas.

One of the used formulas is graphically shown in Figure 2. The figure shows the dependence of emission composition and efficiency on the exceeding air drawn to combustion chamber above the stoichiometric requirement. There is an optimal amount of exceeding air when the efficiency is maximal while the production of harmful CO is minimal. Other than optimal amount of exceeding air causes the efficiency losses and higher production of CO, which is then unable to oxidize to CO_2 and product more heat during the second oxidation. The amount of emitted CO is then good marker of current boiler efficiency (van Loo *et al.*, 2010, Piteľ *et al.*, 2011). However, the optimal amount of exceeding air is not a fixed parameter of a boiler but depends on a current combustion conditions and fuel quality.

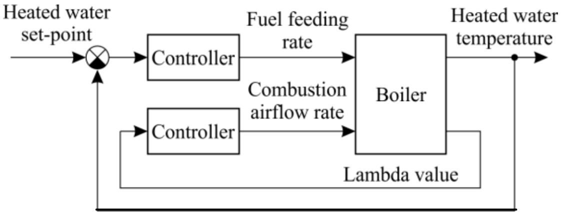

Fig. 4. A scheme of typical control of exceeding air using lambda probe

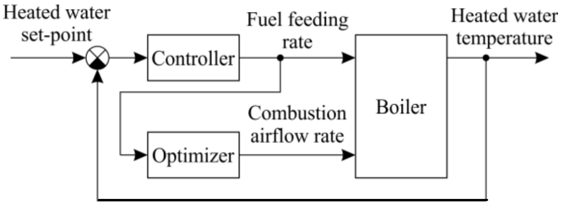

Fig. 5. A scheme of control of exceeding air based of fuel consumption evaluation

Typically, to control the amount of exceeding air, the secondary controller controlling the amount of inlet air is

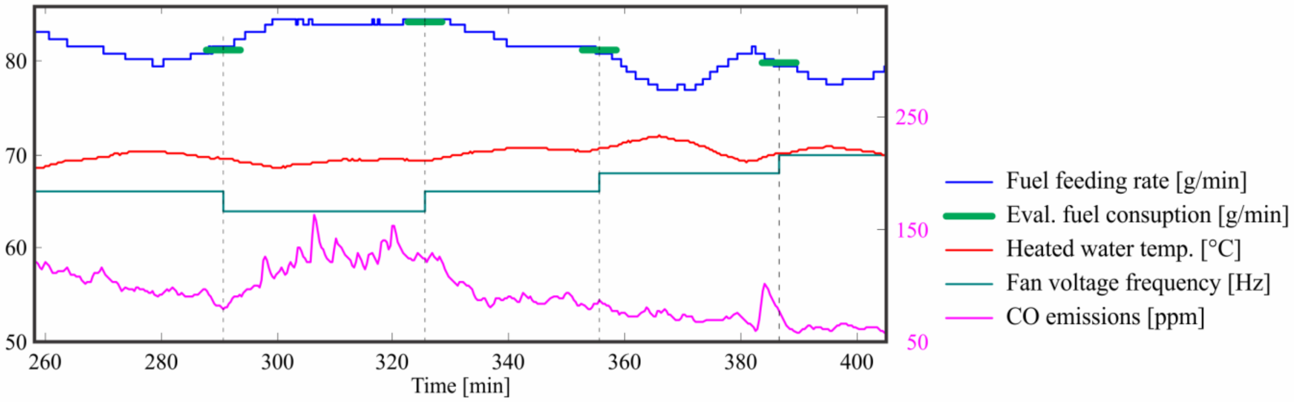

Fig. 6. The course of variables during experiment with exceeding air control algorithm based of fuel consumption evaluation

added to the main controller controlling the amount of fuel (see scheme in Figure 4). The secondary controller action is calculated on base of value given by oxygen concentration sensor, typically a lambda probe (Conte *et al.*, 2006, Piteľ *et al.*, 2011). But this has some drawbacks. Except its costs, it is the lambda probe long time low reliability and high sensitivity to contamination with certain substances (Piteľ *et al.*, 2011). For these reasons, we developed an optimizing algorithm that controls the inlet air fan based on monitoring fuel consumption (see scheme in Figure 5). The optimizing algorithm waits till a steady state is reached and evaluates the fuel consumption needed for the current heat output. Then it increases or decreases the flow rate of inlet air and again waits for steady state and then evaluates the fuel consumption again. This changing of air flow rate and fuel consumption evaluation is repeated till the minimal fuel consumption is found and the boiler operates the most effectively and with minimal production of CO (see Figure 2). The results of lowering the CO emission by the based of fuel consumption evaluation are shown in Figure 6.

It should be noted that similar dependencies to the ones shown in Figure 2 exist also for coal fired boilers (Neuman *et al.*, 1999).

4. EVALUATION OF FUEL PROPERTIES

The boilers, especially the small-scale and often mid-scale ones, are typically operated by untrained operators, the quality of fuel then can vary during operation. The quality of fuel also depends on how it has been stored. This is a case of the wood especially that can contain various percentage of water, if it was not dried before burning. Then, even if the operator uses the same fuel, the burning conditions may be unpredictably different. However, the controller should respect the current fuel quality and choose proper control regime (Piteľ *et al.*, 2012). Because the percentage of water in the fuel influences the amount of produced heat usable for heating the heated water, when the water percentage increases, the proportional gain should increase too to maintain the static sensitivity of the control circuit and other controller parameters should be updated in correspondence. For the control purposes, it is suitable to evaluate the parameters of fuel online. However, the fuel quality evaluation is not possible to be done directly, so indirect indicators have to be used, preferably the ones that are already measured.

There exist relations between the fuel consistency and produced heat by burning this fuel. For the wood, the two are working well, the relationship according to Vondráček

$$\begin{aligned} Q_V^r = \Big(\Big(\big(\big(33.91-2.58C^{daf}\big)C^{daf}+90.88H^{daf}-11.26O^{daf}+ \\ +10.47S^{daf}\big)\big(1-A^d\big(1-W^r\big)-W^r\big)-2.45W^r\Big)\times \dot{m}_f \end{aligned}, \quad (1)$$

and the statistical relation

$$\begin{aligned} Q_S^r = \Big(\big(34.75C^{daf}+95.3H^{daf}-10.9O^{daf}+10.9S^{daf}\big)\big(1- \\ -A^d\big(1-W^r\big)-W^r\big)-2.5W^r\Big)\times \dot{m}_f \end{aligned}, \quad (2)$$

where Q_i^r is the produce heat,

C^{daf}, H^{daf}, O^{daf}, S^{daf} are the ratios of respective chemical components carbon, hydrogen, oxygen, and sulphur in the dry fuel without water and ash,

A^d is the ratio of the ash in the dry fuel without water,

$\dot{m}_f$ is the weight flow rate of fuel,

W^r is the ratio of the water in the fuel (Dlouhý, 2011).

Because the C^{daf}, H^{daf}, O^{daf}, S^{daf} are the ratios of respective chemical components in the fuel without ash and water, they have to fulfil the condition

$$C^{daf}+H^{daf}+O^{daf}+S^{daf}+N^{daf}=1, \quad (3)$$

where N^{daf} is the amount of nitrogen in the dry fuel without water and ash.

As the chemical consistency of used biomass fuel is constant and the ratio of ash in the wood is marginal, the parameter to be evaluated is the ratio of water in the biomass fuel W^r.

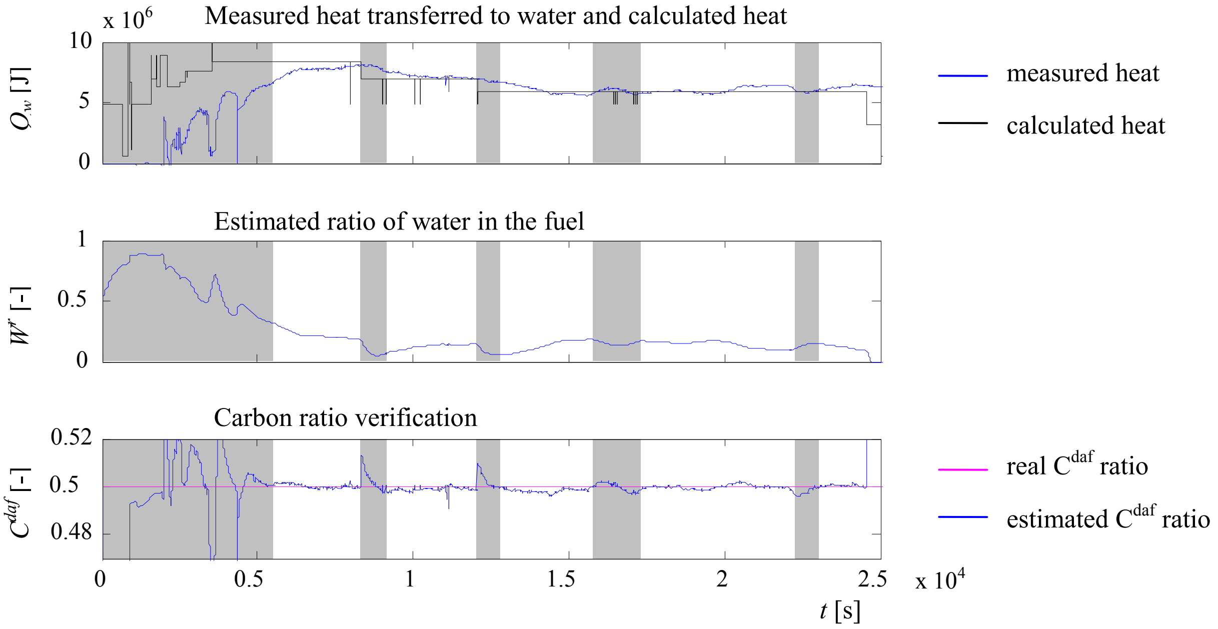

Fig. 7. Result of water ratio W^r estimation

The neural unit has been chosen as a tool for the water ratio evaluation for its undoubtful advantage: it is not necessary to store the past data; all calculations are done only with current data. The feeding mechanism parameters are known and the times for which the feeding mechanisms operates and stops is under control. The inlet and outlet temperature and flow rate of heated water are measured, so it is possible to calculate how much heat was transferred to the water from the equation

$$Q_w = \rho.\dot{V}.c_p\left(T_{out} - T_{in}\right), \qquad (4)$$

where Q_w is the heat transferred to the heated water,
ρ is the density of heated water,
$\dot{V}$ is the volume flow rate of heated water,
c_p is the thermal capacity of water,
T_{in}, T_{out} are the temperatures of inlet and outlet water.

The equation (2) has been implemented into the neural unit and the adaptation rule of the neural coefficient W^r has been derived from Back Propagation learning method as

$$\begin{aligned}\Delta W^r = &-\eta\left(Q_w - Q_S^r\right)\left(1 - A^d\right)\left(34.75C^{daf} + 95.3H^{daf} - \right.\\ &\left.-10.9O^{daf} + 10.9S^{daf}\right)\times \dot{m}_f - 2.5\dot{m}_f\end{aligned}, \qquad (5)$$

The neural unit implemented according these relations identifies the ratio of water in a fuel successfully in the steady states.

The secondary neural unit used for evaluation if the steady state has been reached or not then if result provided by main neural is valid or not has been developed too. It based on equations (2) and (3) and the neural coefficients are C^{daf}, H^{daf}, O^{daf}, S^{daf} adapted while the water ratio coefficient W^r calculated by main neural unit is used. The neural coefficient adaptation rules have been derived again from Back Propagation method into forms:

$$\Delta C^{daf} = -34.75\eta_C\left(Q_w - Q_S^{r*}\right)\left(1 - A^d\left(1 - W^r\right) - W^r\right)\times \dot{m}_f, \qquad (6)$$

$$\Delta H^{daf} = -95.3\eta_H\left(Q_w - Q_S^{r*}\right)\left(1 - A^d\left(1 - W^r\right) - W^r\right)\times \dot{m}_f, \qquad (7)$$

$$\Delta O^{daf} = 10.9\eta_O\left(Q_w - Q_S^{r*}\right)\left(1 - A^d\left(1 - W^r\right) - W^r\right)\times \dot{m}_f, \qquad (8)$$

$$S^{daf} = 1 - C^{daf} - H^{daf} - O^{daf} - N^{daf}, \qquad (9)$$

where N^{daf} is a constant equal to 0.0011 according Tariq and Purvis (1996),
Q_S^{r*} is estimated heat calculated by secondary neural unit.

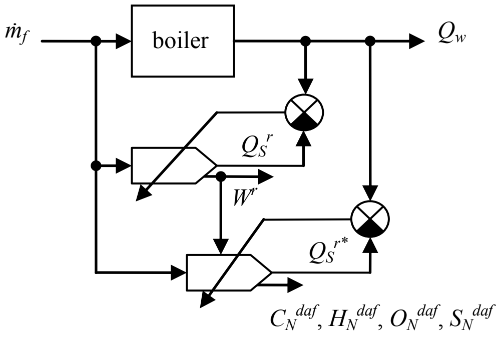

Fig. 8. A principal scheme of neural unit cascade

If the results provided by the secondary neural unit are the same like the known fuel parameters, then the current state is steady and the value of water ratio W^r provided by the primary neural unit is a valid value. The scheme of the neural unit is shown in Figure 8.

The result of fuel property evaluation is shown in Figure 7. The Figure records whole experiment since the fire ignition. The combustion chamber is cold at the beginning of the experiment; the measured amount of heat transferred into the water Q_w then does not correspond to its calculated value till time 0.55x10^4 s. It is because the neural unit does not take into account the heat that is used to warm the combustion chamber; it calculates only with the heat transferred only into the heated water. During this initial period, the estimated water ratio W^r is then not correct. The incorrection is signalized by different value of estimated carbon ratio C^{daf} that differs from its real value. After the combustion chamber is heated, the amount of heat transferred into the water Q_w corresponds to its calculated value and the provided value of water ratio W^r is correct as there is almost no heat transferred into the combustion chamber lining. This is confirmed with a correspondence of estimated carbon ratio C^{daf} to its real value. The periods where estimated value of water ratio W^r may not be reliable because of transient occurrence are marked by a gray background in the Figure 7.

5. CONCLUSIONS

The new control algorithm was developed because the transfer of full-scale boiler control algorithms to the small-scale and mid-scale one has the issues whose solving is comparable time and experience more demanding than the development of new control algorithm.

The deployment of PI controller instead of original hardwired on/off control has positive impact to lowering harmful emissions in the flue gasses and to increase the efficiency of combustion process and then to the economy of boiler operation and environmental friendness. The exceeding air control algorithm proved its ability to reach the minimal CO production which opens the possibility to lower the building costs of the boiler by omitting some instrumentation.

The evaluation of water ratio in a fuel gives the correct result when the combustion process is steady or when the changes are slow. When the transient occurs, the result is loaded by error. On the other hand, the correctness of the result can be confirmed by the additional neural unit, whose output may be used as a measure of size of the error. The algorithm produces incorrect result mainly during a period when the combustion chamber is cold. However, when we count with long term operation of a boiler for many days continuously, the incorrect results at the beginning of operation are acceptable and thus not significant. The undoubtful advantage of neural unit usage is their operation with current data only and then no need to store any past data. The neural unit proved its ability to estimate the fuel structure which opens the way to further development to extend its ability to estimate ratio of other fuel elements.

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