Advanced Features of a Small-Scale Biomass Boiler Control for Emission Reduction

Jan Hrdlička, Bohumil Šulc

***Abstract*—** Small scale biomass combustion is a specific field of control issues where one of the most important features is cost effectiveness. It means that any kind of control system improvement should be done with the lowest possible additional costs. Generally, the basic control of such kind of boiler regulates temperature of outlet heating water. This control can be also performed by a PLC. In such a case, there is possibility to enhance this control by additional algorithms that are responsible for extended optimization functions. Main focus of such optimization should be mainly economic viewpoint of the boiler's operation regarding particularly decrease of fuel consumption and therefore cost saving. Other strong interest is reduction of several unwanted gaseous emissions, mainly carbon monoxide and unburned hydrocarbons. In the interest can be also nitrogen oxides emissions that are much more complicated to control in such a small boiler. This previously minor problem has become significant with the large expansion of the small-size biomass-fired boilers. The combustion process consists of phenomena that we have little information about for an exact mathematical description. The equations of the chemical reactions are known, but in reality the combustion of biomass is much more complicated and more variable than a mathematical model can express. Therefore, techniques searching extreme are more suitable than controllers requiring a mathematical model in design or tuning. In such a way it is possible to design a controller that is able to control the combustion process effectively over the whole operation range.

***Keywords*—** PI temperature control, combustion, emissions, efficiency, fuel consumption

I. Introduction

The question of emissions from small scale combustion systems for biomass has been becoming more important during last years due to a continuous increase of number of such small boilers installed. On the other hand, due to depletion of traditional biomass resources in the Central European region is not expected any further growth in large combustion systems. Because biomass fuel is a local product of relatively low energy density, the future growth is expected at regional level, mostly for household or small industrial building heat production [1]. Even if the biomass combustion is often reported as "green" or "environmentally friendly" compared to coal or oil combustion, this is not generally true. The solid fuel combustion is complicated process that needs to be well controlled to achieve maximal efficiency and low production of gaseous pollutants. Uncontrolled or badly controlled biomass combustion can have more serious impact on the environment than coal or oil combustion. Common example is improper setting of air-fuel ratio during unstable operation regimes of the boiler, e.g. the burn-out phase after reaching the desired value of water temperature or the phase with a suddenly increased power demand.

The term "small-scale" is often interpreted differently in the literature. Here it is represented by the boilers not exceeding power output of about 50 kW. In this range can be found boilers that are mainly used in households or small industrial buildings. From the point of emission regulations, there are no emission limits for such size of boilers. For example, in the Czech Republic are valid operation emission limits established for the boilers with power output above 200 kW. It means that currently are the small boilers out of legal emission inspection. There is only one procedure inspecting ecology of the small-scale boiler's operation – it is the situation of introducing a new boiler to the market. For such a case, there has been adopted an EU-regulation which is the standard EN 303-5. This European standard sets relatively weak demands on the boilers that are newly introduced to the market [2]. For example, the data for automated boilers with the highest efficiency (class 3) is shown in Table 1.

Nominal power output (kW)	**Fuel type: biologic. Fuel feeding: automatic**		
	CO	**TOC**	**Particles**
	mg.m^{-3} at 10 % O_2, dry gas, standard conditions		
	efficiency class 3		
≤50	3000	100	150
50 – 150	2500	80	150
150 – 300	1200	80	150

Table 1: Emission limits according to EN-303-5

Jan Hrdlička: Department of Fluid Dynamics and Power Engineering, Czech Technical University in Prague, Faculty of Mechanical Engineering Technicka 4, CZ-16607 Praha 6, Czech Republic; e-mail: jan.hrdlicka@fs.cvut.cz

Bohumil Šulc: Department of Instrumentation and Control Engineering, Czech Technical University in Prague, Faculty of Mechanical Engineering Technicka 4, CZ-16607 Praha 6, Czech Republic; e-mail: bohumil.sulc@fs.cvut.cz

As it can be seen, there is no valid limit for NOx emissions. Current development in the national legislation indicates that in the future will be established emission limits also for the small-scale boilers. Modern boilers that are nowadays produced easily comply with the requirements mentioned in EN 303-5 standard when introduced to the market. However, the boilers are mostly operated by persons without a specific knowledge about the operation principle. Furthermore, most of the boilers are "controlled" only in the on-off way with the aim to sustain a desired temperature of the outlet heating water [3]. Especially during the unstable regimes, the CO and hydrocarbons emissions can be increased whereas the efficiency significantly drops. This might be taken as a minor problem due to a low power output compared to the large boilers unless it comes to a total number of the boilers installed. According to [4], the total yearly sale of small-scale biomass boilers in the EU is in the range of several tens of thousands, dating back to 2002. With such a number of the boilers, improperly controlled or uncontrolled biomass combustion may have significant negative impact on the local air quality that needs to be solved.

All these facts imply a need to take the ecology of the small-scale biomass combustion seriously into account. Large improvements have been reached during last years in construction of the boilers with the result in significantly increased efficiency. The next step in further operation improvement is control of the combustion process itself. Widely used on-off regulation does not provide enough performance to implement algorithms controlling the boilers not only towards desired heat output but also to minimize the unwanted gaseous emissions. A possible solution using PID controllers with enhanced functions is therefore presented in this paper, focused on minimization of CO and NOx emissions added to power output control algorithm. It employs measurement equipment that can be easily implemented into the boiler without significant increase of costs – temperature measurement by a thermocouple and oxygen concentration measurement by a wide-band lambda-probe.

II. Emissions from Biomass Combustion

There are several kinds of polluting species that are under interest in the combustion process. The first group is connected with incomplete combustion – carbon monoxide and unburned hydrocarbons. The carbon monoxide is formed as a product of oxidation of gaseous hydrocarbons that are released from the fuel in form of volatiles. The general reaction is:

$$C_nH_m + O_2^{\cdot} \rightarrow n(1-\alpha)CO + n\alpha CO_2^{\cdot} + \frac{m}{2}H_2O$$

where α is ratio between CO and CO_2. This quick reaction is followed by carbon monoxide oxidation to CO_2:

$$CO + OH^{\cdot} \rightarrow CO_2 + H^{\cdot}$$

which is strongly temperature dependent. Generally, reaction rate is high enough to oxidize majority of the CO produced at the temperature over approximately 800°C. For the reaction is also necessary sufficient amount of the OH radical. Therefore, the conditions for CO oxidation are sufficiently high temperature in the combustion chamber and amount of combustion air well mixed with the released volatile matter. Oxidation of carbon in a fuel to CO releases approx. 2/3 of the carbon energy content and the final oxidation of CO to CO2 releases approx. 1/3 of the carbon energy content. Therefore is the incomplete oxidation of CO recognized as an energy loss and it is counted in the efficiency of a boiler.

Emissions of hydrocarbons (TOC) also indicate incomplete combustion. Under normal operation, the hydrocarbon emission level is about 10 times lower than concentration of CO for biomass combustion [3]. Growth of the TOC concentration indicates very badly set combustion ratio. For the biomass combustion, the CO and TOC concentrations cannot be predicted in advance by a model because the combustible matter decomposition and combustion is a very complex process with many unknown thermodynamic and equilibrium parameters.

Emissions of nitrogen oxides (NOx) are under interest mainly in connection with internal combustion engines for being an agent acting in formation of tropospheric ozone and photochemical smog from transportation. However, biomass combustion is also significant NOx source. The nitrogen oxides are generally formed in three ways – by oxidation of nitrogen in the combustion air (thermal NOx, Zeldovich mechanism), by oxidation of nitrogen contained in a fuel (fuel NOx) and by reaction of hydrocarbon radicals with nitrogen in the combustion air (prompt NOx, Fenimore mechanism). Rates of all three formation mechanism are in some way dependent on temperature and excess air ratio.

The key reaction for thermal NOx is:

$$N_2 + O^{\cdot} \rightarrow NO + N^{\cdot}$$

which has a very high activation energy to break the nitrogen triple bond. It is therefore strongly temperature dependent and the reaction rate becomes significant at temperatures above 1300 °C. For small-scale biomass combustion this is a minor way of NOx formation. The most dominant way of NOx formation are fuel nitrogen oxidation and to some limited extent also the prompt way of formation. Both these ways are influenced by the temperature (higher temperature supports the conversion) and presence of oxygen.

Dependence of CO, TOC and NOx emissions on the excess air ratio for a case of small-scale biomass combustion is shown in Fig. 1.

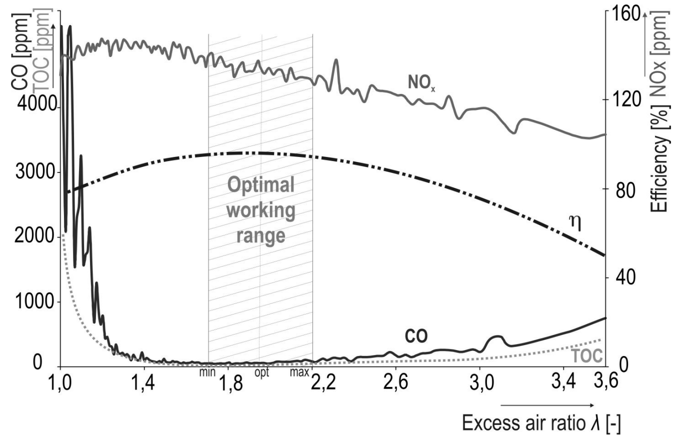

Fig. 1: Dependence of CO, NOx and TOC emissions on the excess air ratio

The emissions of CO and TOC follow the similar trend and are at minimum within certain range of the λ values. When controlling the CO (and TOC) emissions only, the algorithm searches for such λ value at which is satisfied the heat demand with the highest efficiency and the CO and TOC levels are within the optimal range. More complicated situation is for the case with NOx emission control. Within the optimal working range the NOx level is close to its maximum. Therefore it is necessary to search for such λ value where is still satisfied CO level and NOx level is as low as possible. To effectively control the NOx emissions, it is necessary to handle the primary-secondary air ratio as well. This is used for controlling temperature in the combustion chamber. It is however not possible to measure the NOx concentration by an economically acceptable sensor. The control algorithm therefore has to rely on the pre-established dependency curve, as shown in Fig. 1. Nevertheless, NOx level can be predicted with knowledge of fuel properties, temperature in the chamber and excess air ratio.

Thermal NOx formation is described by Zeldovich equation:

$$[NO] = k_1 . e^{-k_2/T} . [N_2] . [O_2]^{0,5} . t$$

where the inputs are N2 and O2 concentrations, residence time t and temperature T. In the literature equation for solid fuel combustion [5] can be also found:

$$C_{NO_2} = (10{,}62.\alpha - 1{,}12).(T - 1573)$$

which is applicable for temperatures above 1300°C. For the small scale combustion can be therefore the thermal NOx formation neglected. The fuel NOx can be estimated by the equation:

$$C_{NO_2} = 2{,}142.\frac{\nu . N^r}{V_{SS}^R}.10^6$$

where the input parameters are fuel nitrogen content Nr, fuel nitrogen conversion ratio ν and volume of dry flue gas recalculated to reference oxygen V_{SSR}. In this equation can be calibrated the conversion ratio by carrying out the NOx measurement.

III. Use of control to optimize operating conditions of a boiler

In the control of combustion devices there are two important considerations – economy and ecology. These two considerations are not the direct focus of control theory, because in the theory, a control circuit is considered to be

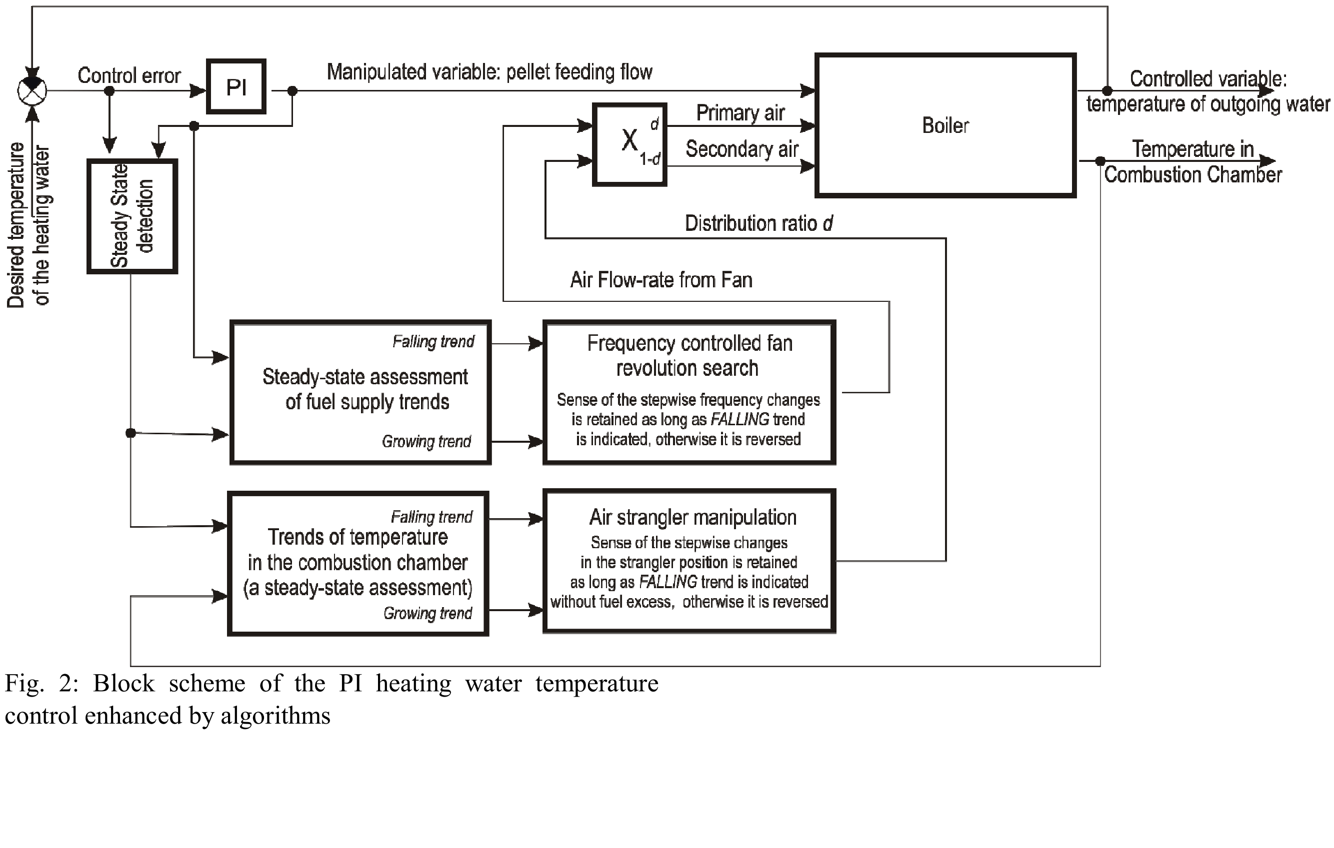

Fig. 2: Block scheme of the PI heating water temperature control enhanced by algorithms

operating optimally if, simply said, during the control process the controlled variable differs from the desired value for the shortest possible time, with the smallest deviation. Control theory is aimed at achieving an optimal course of responses of one or more variables in the control circuit, and direct attention is seldom paid to considerations such as energy consumption or ecological impacts during the control process.

For boilers that prepare water for heating purposes the main task of the control is to maintain temperature of the water delivered in a heating system by a controller manipulating the fuel supply. Suppose that the control loop of this temperature control is designed in such a way that all requirements concerning the controlled temperature of the water are satisfactorily fulfilled. However, the combustion process may run under non-ecological and uneconomical conditions, due to improper values of the combustion ratio. It is not easy to find an optimal setting of the combustion ratio by a conventional controller, because its value changes in dependence on fuel and load.

The desired value cannot be set for the controller in advance. It must adapt to the changing firing conditions. This can be achieved by algorithms cooperating with the standard PI control algorithm inside the controller. The operating strategy of such an enhanced PI controller can be described as follows: keep the controlled variable, whose desired values are known, set these values by the standard PI control algorithm, and during the steady states indicated by unchanging values of the manipulated variables perform an on-line search to set another variable whose optimum is indicated indirectly by means of the extreme in a steady state dependence. The most common interest concerns the output power, the efficiency of operation, the concentration of a specific (emission) component, etc.

Interpreting this general task in notions of optimal boiler operation, the control task can be formulated as follows: keep the temperature of the heating water at the desired value by manipulating the fuel supply in such a way that manipulating the combustion air carried out consequently will lead to a minimum in the necessary fuel delivery, when it is still possible to keep the temperature at the desired value. Then, it can be expected that maximum efficiency in boiler operation has been achieved.

Interpreting this general task in notions of optimal boiler operation, the control task can be formulated as follows: keep the temperature of the heating water at the desired value by manipulating the fuel supply in such a way that manipulating the combustion air carried out consequently will lead to a minimum in the necessary fuel delivery, when it is still possible to keep the temperature at the desired value. Then, it can be expected that maximum efficiency in boiler operation has been achieved.

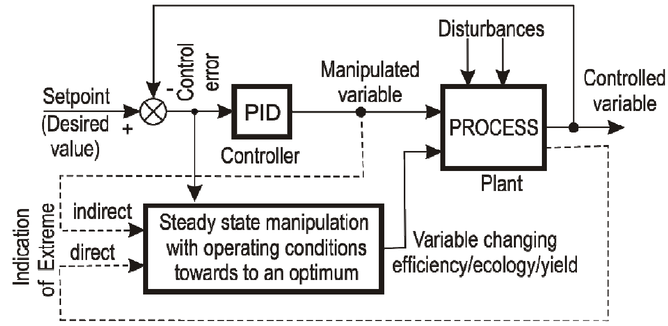

Fig. 3 A general block scheme of a PI control circuit enhanced with optimization of operating conditions

Achieving a minimum of fuel consumption is connected with the minimum of CO emissions because both occur at the same value of the combustion ratio. As it can be seen from the dependencies depicted in Fig. 1, reduction of NOx emissions is a question of a compromise. Proportion of NOx in the flue gases decreases with the growing value of the combustion air that is connected with decreasing temperature in the combustion chamber. However, larger excess air ratio causes increase of heat loss by the flue gas and therefore it has a negative impact on the lost of the efficiency optimum. Therefore we have to admit as an optimum a biased value of the combustion ratio towards to higher values at a border of the optimal operating range. Certain chance for maintaining the optimum offers dependence of the NOx emissions on the temperature inside of the combustion chamber. This temperature and even efficiency of combustion can be influenced by dividing the combustion air into the primary and secondary air. Effect of such distribution depends on design of the boiler, but it can be used of in a control strategy added to the standard PI control of the temperature of the heating water. In comparison the strategy of optimizing fuel consumption which does not require any other instrumentation except that performing manipulation with the flow rate of the combustion air, the strategy of NOx reduction needs to measure temperature in the combustion chamber and instrumentation making possible adjustment of the primary and secondary air from the control unit.

Each of the three control tasks has its own priority. The highest priority has the automatic control of the heating water temperature because it ensures balance between the delivered and consumed heat, while minimizing consumption is an important but second order matter. The NOx reduction requires defining an allowed offset in efficiency, apart from a difficult assessment of the impact that has a change in distribution of primary and secondary air. In such case, use of a lambda probe for a direct evaluation of the combustion ratio can be an important help to achieve the required goal. Otherwise, the whole procedure, graphically depicted in Fig 2 has been proposed to be able to operate without any direct knowledge of the factors that are to be optimized, i.e., no efficiency or concentration are measured, and, full adaptability to changing operating conditions (fuel properties, load, outside temperature etc.) is ensured in this algorithm.

IV. Instrumentation of the Experimental Boiler and Performed Testing

Instead of the pre-programmed fixed logic that is delivered with the boiler, the new RexWinLab-8000 control system was proposed [11]. RexWinLab-8000 is a station based on the WinCon Programmable Automation Controller, which contains five plug-in modules that can be extended. WinCon uses Windows CE as the operating system. The choice of this programmable controller was influenced by the intention to use both REX control system software and Matlab/Simulink support [6] in developing the control algorithms.

The possibility to use Matlab/Simulink has the advantage that all algorithm verification can be carried out on the Simulink simulation model, and verified parts of the developed algorithm can easily be transferred into WinCon using REX software. Therefore the first testing was performed by means of Simulink model where the dynamics of outgoing water temperature changes was modeled by means of the first order transfer functions. These functions were obtained from the step responses measured on the experimental boiler. As it is demonstrated by Fig. 4, accuracy of the models determined in this way cannot be the best one.

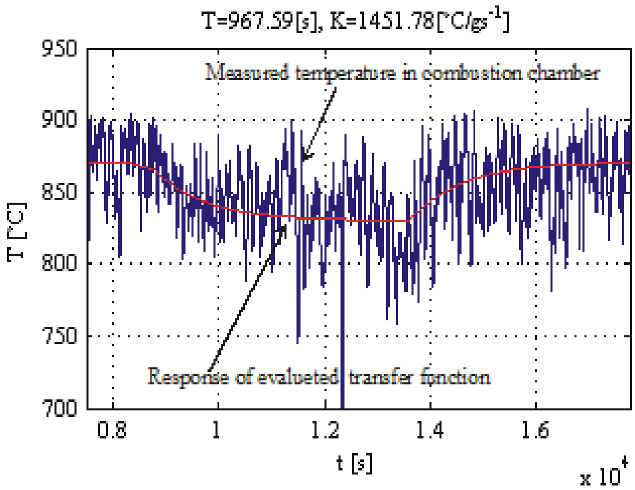

Fig. 4 Recorded data representing measured step responses and their approximation using a linear model

The main aim of the modeling was to verify the feasibility of the proposed concept when an additional optimizing function towards emission reduction was to be applied. Direct testing on the experimental boiler had little chance to be carried out because each search step took more than one hour and the experiment could be done only during standard working hours. Therefore simulation was advantageous in this case, nevertheless some experiments verifying at least the optimization of fuel consumption were carried out.

Correct function of the fuel consumption optimizing algorithm can be demonstrated by Fig. 5. Depicted course of the manipulated variable as a measure of the fuel feed goes gradually down while all the time the temperature of the heating water is constant (see Fig. 6). Decrease of fuel supply, which would normally cause decrease of the boiler power, is compensated by improvement of burning conditions based on changes in the combustion ratio resulting from the changes in air supply setting.

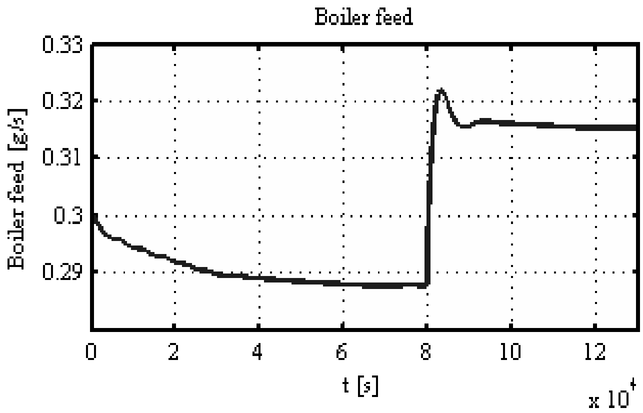

Fig. 5 Lowering of the fuel supply as a result of o the combustion process optimizing

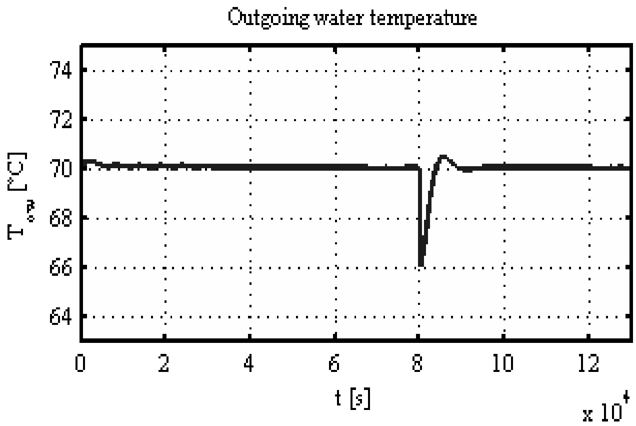

Fig. 6 Temperature of the outgoing water

In the algorithm performing the fuel optimization, two pieces of information are used as inputs: one piece of information concerns detection of steady states in the main control loop based on recognition of the control error close to zero, while the second assesses the trends in the fuel feed evaluated as the difference between steady values in the previous and current steady state values of the manipulated variable. The output of the optimization algorithm is represented by the step changes in the revolutions of the fan. These changes are generated only after the control error value is close to zero. The activities described here were performed in the simulation model. At time 8000 s, when a change that has been introduced into the flow rate of the heating water simulating a change in the load of the boiler, the PI controller had to react to a drop in the outgoing water temperature by increasing the fuel feeding. This caused shift in the combustion ratio and a new search for the optimal value had to be started.

After these experiments and preparation, some long-time runs verifying functionality of the proposed optimization algorithm in two stages have been carried out. First set of runs consisted of initial testing of the algorithms. Results from the experiments are shown in figures 7 to 9, showing progress of fuel consumption, outlet water temperature and trend in CO and O2 concentrations in the flue gas

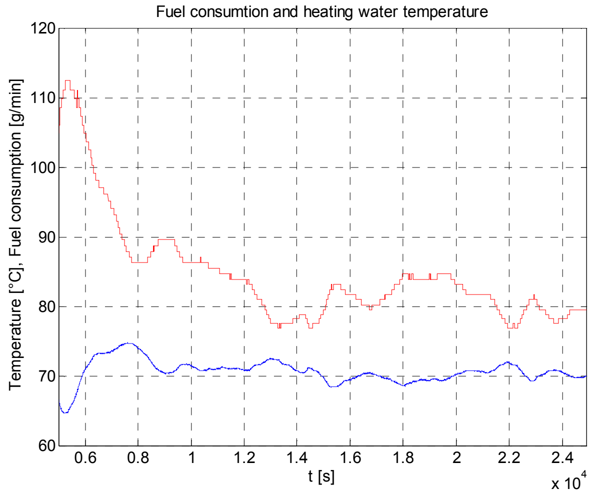

Fig. 7: Run 1, trends of water temperature (setpoint 70°C) and fuel consumption

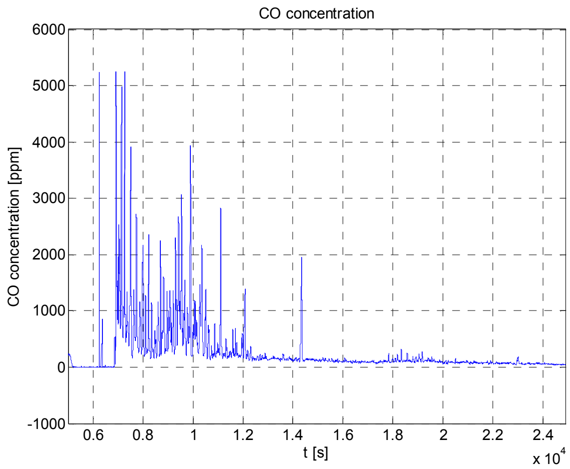

Fig. 8: Run1, carbon monoxide trend during optimization

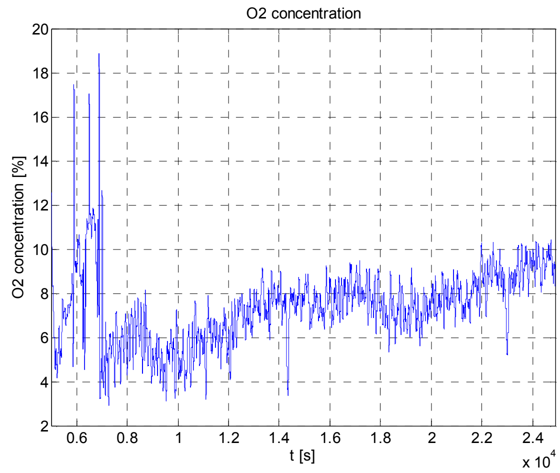

Fig. 9: Run 1, oxygen concentration trend

The optimization process has been started on the left side of the optimum point, i.e. at lower excess air ratio, as shown in figure 1. As soon as the basic control of outlet water temperature is finished (approx. in time 10000 s from the beginning of the experiment), the optimization algorithm starts to stepwise increase air flow which resulted in decrease of fuel consumption and CO reduction. Due to certain problems this run has been terminated before reaching the optimum. Therefore the run has been repeated and the results are shown in figures 11 – 12.

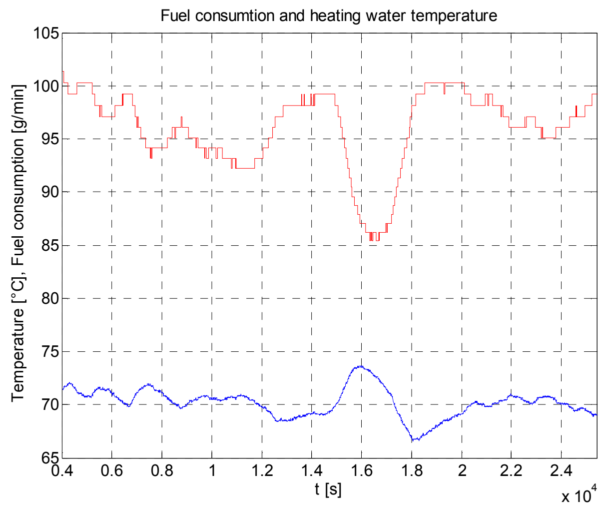

Fig. 10: Run 2, trends of water temperature (setpoint 70°C) and fuel consumption

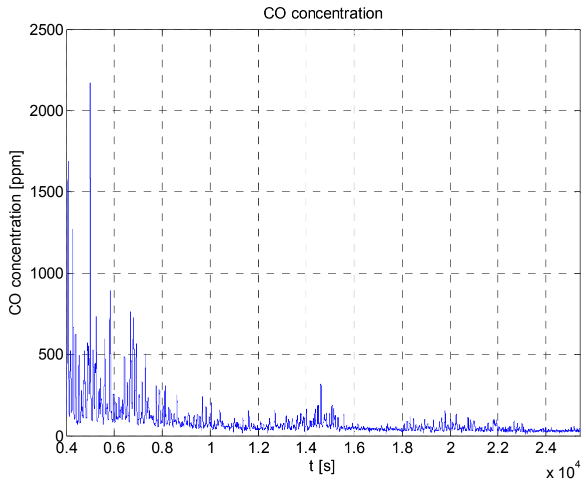

Fig. 11: Run 2, carbon monoxide trend during optimization

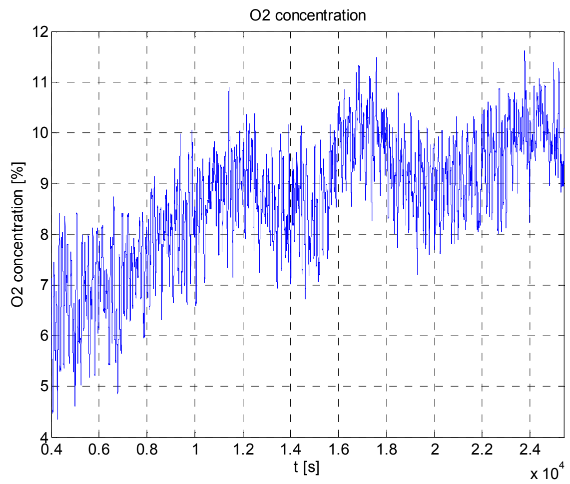

Fig. 12: Run 2, oxygen concentration trend

In the run 2, the optimization process has been interrupted by sudden water temperature increase. The optimization has stopped because of water temperature out of steady state range and the PI controller begun to regulate the temperature back to the setpoint 70°C. After reaching a new steady state, the optimization continued, reaching the desired optimum. It can be seen in large reduction of CO concentration and oxygen concentration around 9 % which is exactly in the optimal working range, as shown in the figure 1.

V. Conclusion

It has been shown that enhancement of the boiler control with algorithms that operate towards emission reduction has to respond to very complex and sometimes contradictory conditions. The CO and hydrocarbon production is directly related to the optimal excess air ratio and consequently to the temperature in the combustion chamber, which reaches maximal level at low CO production. The algorithm assumes that if the maximum in the efficiency has been reached, the CO and hydrocarbons would also reach the desired minimum level. It means that it relies on the known dependency of CO and hydrocarbon level on the lambda value. However, when the algorithm is supposed to decrease NOx level as well, the conditions become contradictory. In the lambda region of the highest efficiency and the lowest CO and TOC, the NOx level is near to a maximum. Furthermore, the NOx is dependent on both lambda value and the temperature in the combustion chamber in a way that cannot be easily predicted. In the paper have been shown approximate prediction equations that usually overestimate the NOx level, however. A possible solution is determining the NOx curve (as shown in Fig. 1) by an experiment that can be done for the certain type of boiler and fuel in the factory. The results may be then used for calibration of the predictive equation. The algorithm would then work in a way to offset the optimal lambda value to a level where the efficiency is still satisfactory. In parallel the algorithm follows the NOx prediction curve to find the minimum value that is still within the satisfactory efficiency, CO and TOC levels.

The first results both from simulation and tests on the real boiler show that the idea of optimizing the operating conditions with guaranteed control of the heating water temperature is feasible. The basic optimization algorithm will have to be equipped with other precautions before it is applicable for real boilers. We have a pilot boiler available, and we assume that we will be able to create step by step more complex, but also more credible models, enabling us to prepare harder conditions in the enhanced controller tests. Successful application of controllers equipped with a combustion optimizing function can be very attractive both for producers and for users because it does not require any special knowledge and skill as far as setting is concerned, and at the same time economical and environmentally friendly operation with special focus on low fuel consumption and low emission levels is achieved automatically and for different fuels.

The simulations have been verified by two long-time experimental runs employing the optimization algorithm. The boiler has reached the optimal operation range with corresponding oxygen concentration around 9 – 10 % and reduction of carbon monoxide emissions from initial average of approx. 300 – 500 ppm to average concentration at 50 ppm. As the most important result, there has been reached reduction of 5 % in fuel consumption. This might look as not large amount, however in a yearly operation of a middle-size family house it can make approx. 500 kg of pellets which in average might save amount around 150€.

Acknowledgement:

This research had support within Project MSM 68400 770035 "Development of environmentally friendly decentralized power systems".

References

[1]M. Lackner, Winter, F., A. K. Agarwal, eds.. Handbook of Combustion, Vol. 4, pp 85– 36, Wiley-VCH Verlag, 2010.

[2]EN 303-5: Heating boilers, 2000
[3]M. Kaltschmitt, H. Hartmann, H. Hofbauer Energie aus Biomasse, Springer, Heidelberg, 2009
[4]The RES-H Initiative and related directives Heat from Renewable Energy Sources, available http://ec.europa.eu/environment/climat/.../ renewable_energy_srcs_heat.pdf
[5]Z. Ibler, Karták, J.: Emise oxidů při spalování fosilních paliv (in Czech). Energetika 40, 1990, 7
[6]B. Šulc, S. Vrána, J. Hrdlička, M. Lepold Control for Ecological Iimprovement of Small Biomass Boilers, IFAC Symposium PP&PS, 2009, Tampere,
[7]B. Šulc, Assessment of Excited Oscillation in Controller Parameter Setting, WSEAS Transactioms on Systems and Control, 2006, Vol. 1, No. 2, pp. 129-134. ISSN 1991-8763.
[8]B. Šulc, D. Klimánek, Evolutionary Algorithms in Supervision of Error-Free Control. In: Soft Com
puting Applications for Database Technologies. (K. Aubumani, R. Neduncheyhian, Eds). Information Science Reference, Hershey .New York, 2010.
[9]B. Šulc, S. Vrána, Some Observations on Develop
ment and Testing of a Simple Autotuning Algorithm for PID Controllers, WSEAS Trans. on Systems and Control, October 2009, Vol. 4, Issue 10, pp. 497-508. ISSN 1991-8763
[10] S. Vrána and B. Šulc, Control Quality Indicators in PID Controller Autotuning, CITSA 2007 jointly with CCCT 2007, vol. II. Orlando: International Institute of Informatics and Systemics, 2007, pp. 280-285.
[11] J. Hrdlička, B. Šulc, S.Vrána, V. Plaček Ecological Aspects of Small-Scale Biomass Combustion. Int. Conf. on Development, Energy, Environment, Economics (DEEE '10). New York: WSEAS Press, 2010, p. 388-393. ISBN 978-960-474-253-0.
[12] J. Boržíková, J. Piteľ, P. Skok Mathematical Description of the Complete and Incomplete Woodchips Combustion. In: Mathematical Methods in Technics and Technologies MMTT-23, Saratov, Russian Federation, 2010, pp. 39 40