Impact of Control Solutions on Ecology and Economy of Small-scale Biomass Boilers

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***Abstract*—**Using an experimental platform for research of combustion process in small-scale biomass boilers using pellets, authors present some results from investigation focused on improvements of boiler's operation, which can be achieved with a control system innovation based on a PAC. Presented results include reduction of the size in emission peaks that occur as a consequence of the grate movement process that has not been adapted to the topical load. This instrumentation replacement allowed implementing a PI control algorithm that has replaced the originally installed on-off controller. The newly proposed PI controller opens new way to additional control function that can bring enhancing features to the control system. From these features, in the paper it is discussed detection of the controlled variable discredibility or a search for an efficiency or emission optimum simultaneously carried out with the main control function. Results of experiments with original and newly designed control solutions are discussed showing important reduction of the fuel consumption and stability of the combustion process.

***Keywords*—**biomass, combustion, control, emissions, efficiency, sensor, small–scale boiler

I. INTRODUCTION

The question of ecology of small scale combustion systems for biomass is becoming more important during last years due to a continuous increase of number of these systems 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. In the Central European region, there are several regulations for gaseous emission from small-scale biomass combustion, i.e. boiler with the power output below 250 kW, depending on the national legislation. However, the only EU-adapted regulation is standard EN 303-5 that sets relatively weak demands on the boilers that are newly introduced to the market [2]. Modern boilers easily comply with the requirements mentioned in this standard. However, the boilers are mostly operated by persons with minimal knowledge about the operation principle. Furthermore, most of the boilers are "controlled" only in the on-off way with the aim to sustain 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. Some of the national legislations in Europe have included emission limits also for small scale boilers to allow monitoring of the local pollution sources. However, practical application is quite complicated and limited due to the fact, that the operators of such boilers are private persons without special knowledge.

Another reason for further improvement and enhancement of control systems for small-scale biomass boilers is economy. The main operation costs of such kind of boiler are fuel expenses. Important reduction can be naturally achieved by decreasing the consumption; however, there is still space for a fuel consumption reduction by enhancing abilities of process control.

This paper therefore focuses on the ecology and also economy problems from the point of control. There is a need to change the typical on-off control that is more or less operator dependent to the controllers acting continuously that are able to achieve simultaneously controlled values of the required heat output and optimal conditions for the combustion process from both the emissions and efficiency point of view. There are not so many papers reporting the small-scale biomass boiler control issues for reference. An overview of the small-scale biomass combustion control has been presented by [5] and control issues of combustion of wooden pellets that are used in the experiments, have been reported e.g. by [6 - 8] and [11].

The statements mentioned above mean that there are two strong motivations for developing and applying more advanced control. For economic reasons, the boiler should be as efficient as possible. Then, there is strong tendency to establish tightened emission limits, even for small-scale boilers. Of course, the costs of necessary instrumentation for developing such advanced control must be taken into account, because the price of the boiler must be competitive with the price of similar products. It is therefore important to design several technical solutions and to test them on a pilot boiler with rich instrumentation, so that an objective comparison can be made before starting production.

II. CONTROL OF EMISSIONS FROM BIOMASS COMBUSTION

Combustion of solid fuel in a grate furnace runs in several steps that are distinguished by the temperature profile. When the solid fuel enters the combustion chamber, firstly it is heated up to around 100°C when evaporation of moisture begins. The heat release in the chamber quickly warms up the fuel element to higher temperatures around 250°C when begins the release of the volatile matter. In the combustion chamber conditions the release is very rapid and the volatile matter quickly ignites. During the volatile matter combustion, the temperature of the fuel element reaches its maximum and combustion of the fixed carbon begins. The maximum temperature level depends on properties of the fuel and on the excess air ratio.

The stages of fuel combustion require taking several precautions to reduce incomplete combustion, which decrease the boiler’s efficiency. The first step is the fuel input into the combustion chamber. Generally, the more fuel is introduced in a single moment, the more heat is needed to evaporate the moisture contained in the fuel. The good approach in this case is more continuous fuel feeding, i.e. smaller amounts of the fuel for a longer period of feeding. This is in contradiction with the real behavior of those controllers that usually allow only a timed feeding with fuel batches. The most important point regarding combustion efficiency is the volatile matter release and burning. The rapid release of volatiles means that there is necessity of a quite large amount of air to be mixed with the released gas within the hot zone. If the air is not available, then the volatiles do not burn completely and are in form of carbon monoxide and hydrocarbons released to the flue gas without using their energy content. From this point of view a reasonable solution is to introduce the combustion air above the fuel layer to mix well with the released volatiles. However, there still remains the fixed carbon that is in solid form on the grate. Therefore the combustion air is splitted into two streams, one passes through the grate for the fixed carbon combustion, the other stream is injected above the grate level to burn the volatiles. A big task to solve by the control algorithm is balancing the correct distribution of the primary and secondary air streams; however, these types of boilers do not deal with this issue. The most modern boilers are equipped with a manual possibility to set the primary/secondary air ratio, but this is not actively controlled, even if it would be a marginal cost in relation to the overall price of the boiler. To verify if the air ratio is properly set is possible to carry out measurements of temperature field across the combustion chamber combined with measurement of oxygen, carbon monoxide and hydrocarbons in the flue gas. Uniform temperature distribution by the high at low CO concentration indicates that the air ratio is correct. Any temperature imbalances indicate an opposite situation, e.g. a too low temperature in the post-combustion zone together with a too high oxygen content in the flue gas indicate that there is too much secondary air that cools down the combustion chamber.

The gaseous pollutants that are under legislative regulation are CO, NO_x, SO_2, TOC and particulate matter. The EN 303-5 standard sets the limits for CO, TOC and particulate matter only. SO_2 emissions can be neglected due to low sulfur content in the biomass and NO_x emissions cannot be effectively controlled in small biomass boilers. Efficiency of the boiler and the emissions of CO, TOC and NO_x are dependent on the excess air ratio α, as shown in Fig. 1. The excess air ratio is a measure of excess of the combustion air amount related to the stoichiometric conditions and it is defined by following equation:

$$\alpha = \frac{V_{air,real}}{V_{air,stoichiometric}} \tag{1}$$

It is usually obtained indirectly by measuring either oxygen or CO_2 concentration instead of the direct measurement of the combustion air flow rate, which would require costly equipment. The most common way of obtaining the alpha value is use of the oxygen concentration measurement by a so-called lambda probe, which is generally an oxygen analyzer working on the principle of the electrochemical cell. The alpha value can be then obtained as follows:

$$\alpha = \frac{21}{21 - C_{O_2,measured}} \tag{2}$$

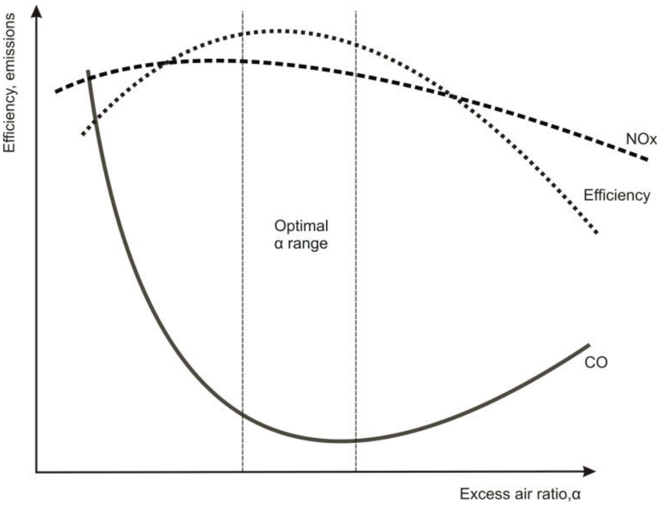

Fig. 1: Efficiency, CO and NO_x dependency on excess air ratio – typical trend scheme; TOC concentration follows the CO trend.

The CO dependence on the excess air ratio for a small-scale biomass boiler has been also measured by [8] and it is shown in Fig. 2. The measured data is approximated by use of Neural Network Fitting Tool offered by Matlab program package.

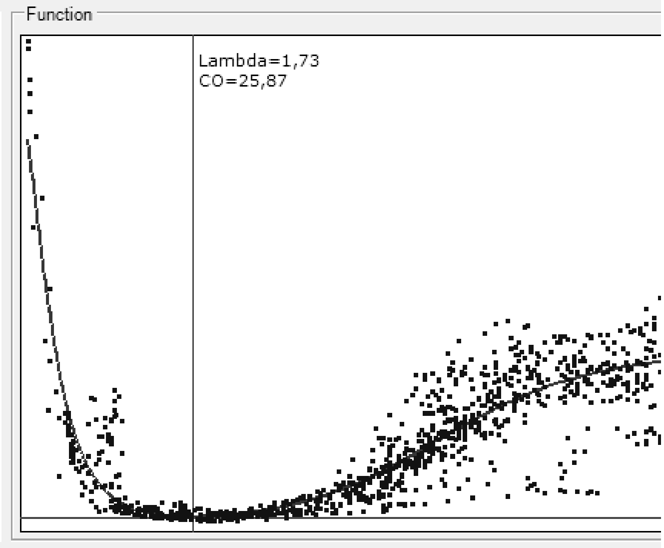

Fig. 2: CO concentration dependency on excess air ratio α [8]

The on-off thermostatic control units that are the most common in the small biomass boilers do not respect the situation depicted in Fig. 1. They usually work with a pre-set fixed excess air ratio that cannot be changed by the control unit. The simple control unit is generally able to control amount of the fuel fed into the boiler which is used for heating water temperature control. The same mechanical device is used to perform grate sweeping that removes ash from the grate. These processes are discontinuous and they cause some sudden changes - disturbances in otherwise continuous operation of the boiler.

III. Possibilities of Control System Enhancement

One of the possible concepts is economy and ecology of operation of a boiler, which have not been previously under considerations in on-off control systems. In theory, a control circuit is considered to be 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.

A good example of ECO control is offered by combustion devices, represented by boilers that prepare water for heating purposes. The temperature of the water delivered in a heating system is controlled by a controller manipulating the fuel supply. 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 an algorithm cooperating with the standard PID control algorithm inside the controller. The operating strategy of such an enhanced PID can be described as follows: keep the controlled variable, whose desired values are known, oat these values by the standard PID 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. It is even possible to define a compromise between boiler efficiency and the proportion of harmful components in the flue gases by means of an enhanced weighted criterion. Some tests of this optimized PI control have been published in [14].

The other controller enhancement possibility concerns automated parameter tuning. An approach is proposed which attempts to meet most of the requirements of industrial practice. The proposed method is based on an experimentally performed evaluation of small amplitude excited frequency responses with the aim of achieving recommended values of one or more control quality indicators known from the course of the Nyquist plot, e.g. [12], As regards the experimental way of obtaining the indicators, they can be evaluated in control loops involving nonlinearities even in the controller. In this sense, the method has a philosophy similar to that of the popular Ziegler and Nichols method, but no interruption of the control process is necessary and the amplitude of the excited oscillation is fully selectable. The main advantages of the method presented in [13] are: no use of any mathematical model, usability as an addition to an existing controller purely via the software, and no necessity to break the control process during controller retuning.

The mentioned enhancements can be introduced only in boilers being equipped with programmable controllers. The focus of attention in this paper is on the chances of the concept for controlling combustion devices represented by small biomass heating boilers, a pilot sample of which was made available to us.

IV. Experimental Boiler

The advanced continuous control regarding the efficiency and emissions optimization has been developed and tested on a commercially available boiler. The boiler is designed for combustion of wooden and alternative (e.g. grain, hay) pellets of diameter 6 – 8 mm. Nominal power output of the boiler is 25 kW for wooden pellets. For all experiments 6 mm softwood pellets have been used. The boiler consists of a lined combustion chamber located in the bottom section and a system of heat exchangers in the upper section. A steel grate with the primary air inlet from beneath is placed in the combustion chamber and the secondary air inlet holes are located in the side walls of the chamber. The primary/secondary air ratio is adjustable by a flap; however, there is only one air fan. The pellets are fed from a storage container by a screw feeder to the grate. By using the original on-off control unit of the boiler, feeding of the pellets is done periodically with preset periods of screw feeder movement and idle state. During the operation, also the grate is periodically moved (swept) in the way that the pellets are moved towards end side of the combustion chamber. In optimal case, the pellets are completely burned out when they reach the end of the chamber. The ash is afterwards collected in the ash container. The combustion air is fed into the boiler by an air fan, which is originally impulse-controlled and allows a manual adjustment to four different air flow rates. The boiler has afterwards been equipped with several measurement and indication points, as shown in Fig. 3.

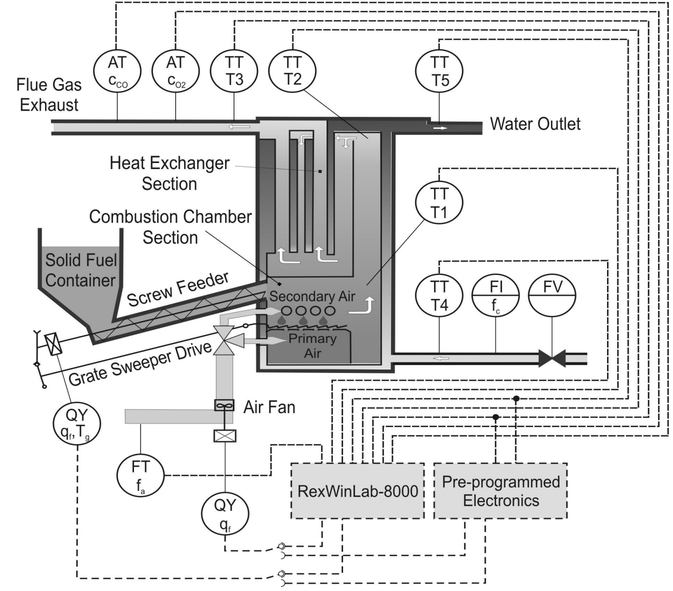

Fig. 3: Scheme of the boiler with additional measurement equipment

The boiler was originally equipped with a control unit that only allowed a very limited intervention in the combustion process. A newly designed switchboard was therefore connected parallel to the original control unit and additional measurements points were included. The switchboard is equipped with RexWinLab-8000 control and data acquisition unit which is developed along with the switchboard at Department of Instrumentation and Control Engineering at the Czech Technical University in Prague. The RexWinLab-8000 is based on PAC (Programmable Automation Controller) Wincon 8000 series, but the control firmware of the PAC is replaced by software named REX Control developed at Institute of Cybernetics at University of West Bohemia in Pilsen. The REX Control software allows using advanced control algorithms commonly unavailable in standard controllers. It has also its own graphical user interface based on similar principles as program Simulink produced by MathWorks. Also a real-time communication with programs in Matlab/Simulink is possible.

The new configuration allows preparing experiments in advance on a standard PC. Any control algorithm synthesis can be easily realized in the graphical development environment, which is very similar to the well known Simulink. Data from all sensors placed in the boiler sensors are time-synchronized and centralized to PAC. During the experiment PAC sends measured data to program Simulink running on a remote computer. Data is periodically saved in Simulink for further off-line analysis. The described development of the switchbox with RexWinLab-8000 changed the standard factory boiler to an experimental base that allows preparation, monitoring, interfering, data acquisition and analysis during the experiments in real-time.

V. OPTIMIZATION OF GRATE SWEEPING

The grate sweeping is one of the key factors that influence the emissions. During the idle period, the fuel is being accumulated on the grate forming a layer which has the fresh fuel on the top side and slowly burning charcoal at the bottom. At the bottom, the fuel is not well mixed with the combustion air. When the grate sweeping operates, the bottom layer is moved forwards and causes sudden changes - disturbances in the combustion process. The nearly fresh fuel is mixed with the charcoal causing flame suppression for a certain time period until a new balance is established. During this period, temperature in the combustion chamber decreases while the CO concentration and also the oxygen level increase. If the original control unit is used, this grate sweeping is well reflected as the periodical strong peaks, as shown in the left part of Fig. 4. This phenomenon is not only a source of the higher CO concentration but it also makes complications in control. One of the possible solutions of this issue was to shorten the grate sweeping period making the grate to travel shorter distance, thus less disturbing the combustion process. Consecutively, the time interval between the grate has been also shortened to keep a sufficient ash removal from the grate. The result of this change is shown in Fig. 2, right side.

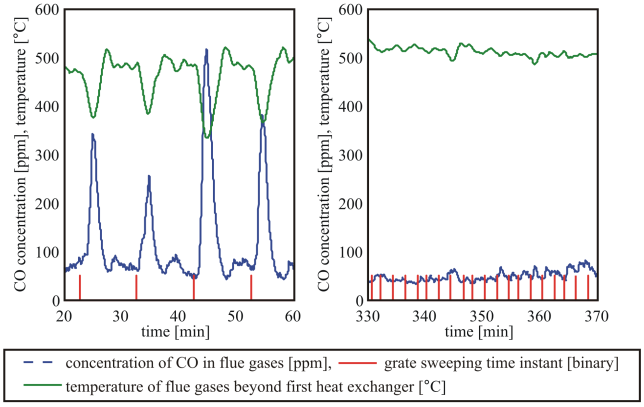

Fig. 4 Comparison of CO concentration and temperature responses obtained with the original (left) and improved (right) grate sweeping algorithm (grate sweeping time instants are marked in both records)

VI. SENSOR FAULT DETECTION

Another issue concerning ecology of the small-scale boiler operation is validity of the signals provided by the key sensors that are used for control of the boiler. There are two of them that are of the main interest – the temperature sensor and the oxygen sensor. For the case of the experimental boiler, there have been used for newly designed continuous control the temperature after first convective section of the boiler (marked as T2 in Fig. 3) and oxygen concentration, measured by a lambda-probe (marked as C_{O2} in Fig. 3). From these two, the oxygen concentration is more important for the ecological reasons, according to Fig. 1 and 2, because the CO and TOC response are very sensitive to changes in the oxygen concentration. This is shown in Fig. 4 in more details, where is depicted a time record of the boiler operation data using the newly designed control system. There, relatively small variations of oxygen concentration (red line) in the range of units of volume percents can be well identified. But these variations can cause large changes in CO concentration, which is one of the direct identifiers of incomplete (and therefore less efficient) combustion. These changes are also found in T2 values (thin azure line marked as temperature above the heat exchanger) that are tightly bound to the excess air ratio value. However, there is no major influence of the T2 temperature on the boiler's operation (the desired outlet water temperature) because these fast temperature variations are well compensated by the heat accumulation in the boiler.

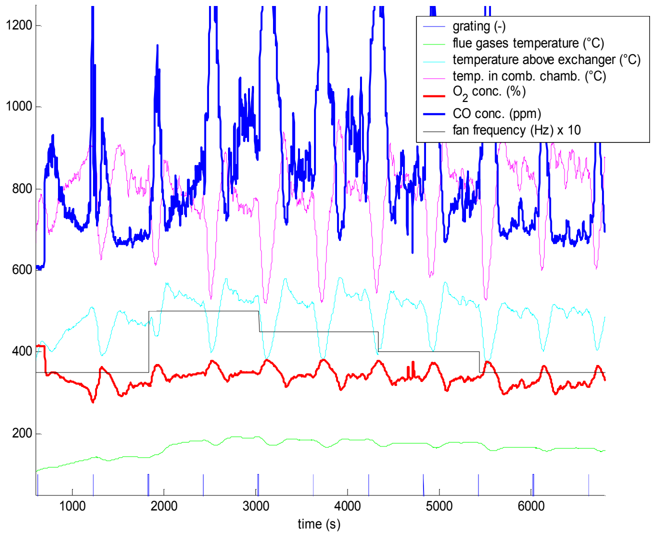

Fig. 5 Time record of several variables characterizing boiler operation as responses to changes in combustion air flow (done by changes of the air fan motor frequency)

Due to the principle of the lambda probe, it is possible that there may appear slow continuous change in response of the sensor. In such a case, the lambda-probe provides gradually wrong reading of the oxygen concentration. Such situation is called discredibility. Generally, if the property changes of the oxygen sensor do not lead to a total sensor failure, it is difficult to recognize that the sensor is providing slightly wrong measurements, because from the outside viewpoint the combustion control seems to be working properly. However, as it has been shown in Fig. 1 and 4, even a small change of the oxygen concentration may cause to move the CO concentration and efficiency out of the optimal working range. If the gradually increasing malfunction has not been recognized, operation of such boiler can easily be out of the optimal range. Such situation reflected in the control system of the boiler is shown in Fig. 6. For better illustration, a sudden change of the lambda probe functionality is supposed. By means of the responses in the temperature control circuit (the upper part of Fig.6) and oxygen control circuit (the lower part of Fig. 6), it is demonstrated what happens after the change of the lambda probe functionality. In the oxygen control circuit, this change in the data provided by the lambda probe is evaluated as a control error change which starts to be removed by the change in the combustion air (in the depicted case it is increased because a positive control error corresponds to the virtual "drop" in the O_2 concentration). As the consequence of the real change in the combustion air flow the temperature starts to change and the control loop for its control recognizes this as a temperature control error. It reacts by adding more fuel to ensure the desired temperature. In fact, the amount of the air has not needed to be changed. However, the alpha ratio has moved out of the optimal working range. Result of this situation can be an unwanted raise of gaseous emissions (CO, hydrocarbons) and a decrease of efficiency, while the temperature is still kept on the desired value after all, thus from the operation viewpoint everything is all right because both of only by means of sensors checked quantities show right values.

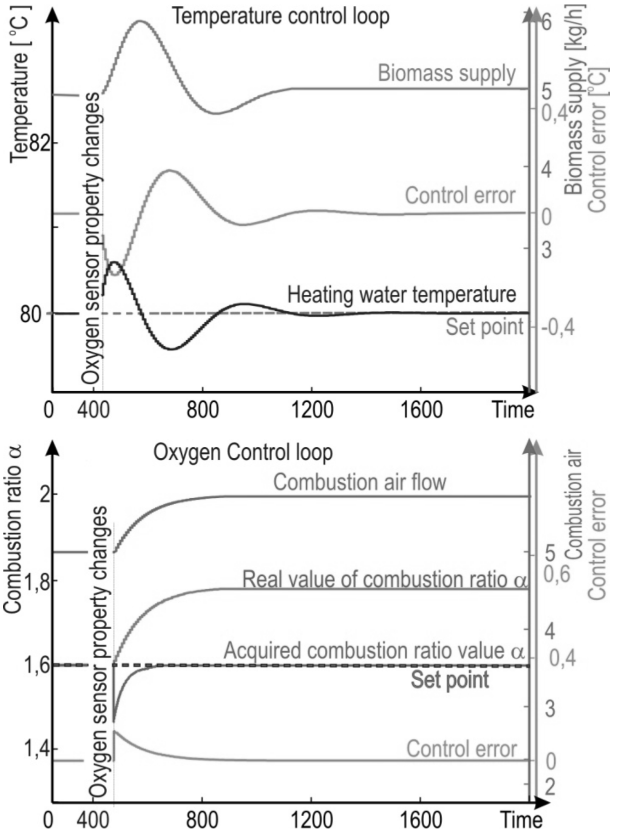

Fig. 6 Impacts of changes in the oxygen sensor response on the control loop signals

The discredibility of the sensor can be detected either by installing an additional sensor or by software detection. The additional sensor is not suitable due to increased cost of the boiler. Therefore the extended function of the control loop based on model of the sensor behavior is the efficient solution. The proposed model-based sensor discredibility detection method is based on the model of the control variable sensor:

The main advantage of such a solution is that all necessary data is already available from the technological process.

The general requirement for a successful application of the method is to design a so-called objective function. In terms of sensor discredibility detection, this function is called a residual function or a residuum $e(t)$ (the difference between the output of the sensor model and the real sensor output).

During discredibility detection, the residuum is minimized via sensor model parameter adaptation. Basically, if the change in the sensor model parameters exceeds the limit of the tolerance range, the operator can be informed in advance to perform any further measures or precautions.

VII. COMPARISON OF CONTROL SOLUTIONS IN THE SMALL-SCALE BIOMASS BOILER

As it has been already mentioned, the most common way to control such boiler is on-off control. In principle, from the control is required to keep the desired temperature level of the outlet water, which is used for heating. The control unit uses the only signal from temperature measurement of the outlet water. This temperature is set manually by the user according to his/her heating requirements. The on-off control works in the way that in certain intervals it switches on and off the fuel feeding. The intervals between feeding and its time duration are usually factory preset and the user cannot change them. The initial intervals are kept until the desired temperature is reached. After that, the control unit switches the feeding to a low-power mode, i.e. it suppresses the fuel feeding only to keep burning on in the combustion chamber. This is followed by a water temperature drop. If the drop is larger than 10 °C, the control unit starts to feed more fuel to reach up the water temperature back to the set point. If the power output is constant (i.e. the heat consumption is constant) this procedure repeats periodically while the desired set point has been never stably reached. We have described in detail this situation by using the experimental boiler with the specific measurement equipment. Result of this experiment is shown in Fig. 7. The desired temperature set point was in this case 90 °C, according to the original manufacturer’s setting.

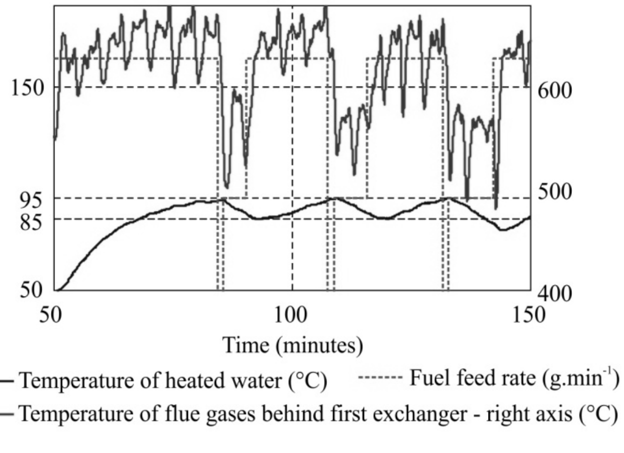

Fig. 7 Operation of the on-off control unit

From the graphs in Fig. 7 can be clearly seen how the outlet water temperatures varies around the desired set point in range of approx. 10 °C. The red line shows temperature after the first heat exchanger (T2 in Fig. 2) that also varies in the range from 50 to 80 °C. These sudden step changes in fuel feeding and consequently the changes of the temperature in the combustion chamber (identified here by the T2 temperature) cause instability in the combustion process that results in increased CO and hydrocarbons emissions and dropped efficiency. Consequently, the dropped efficiency means a higher fuel consumption to sustain the same heat power transferred to the heating water. We have therefore proposed a PI (proportional-integrative) controller that has been programmed into the RexWinLab-8000 Measurement and Control Station. The PI controller adjusts fuel feed control regulating boiler heat input and thus affects temperature of the heated water. A simple thermo mechanical steady-state model was created and with help of the data from previous experiments, a simple mathematical model was estimated. Based on the estimated model, the parameters of the PI controller were determined using Compensation of Dynamics method [9]. The PI controller circuit scheme is shown in Fig. 8.

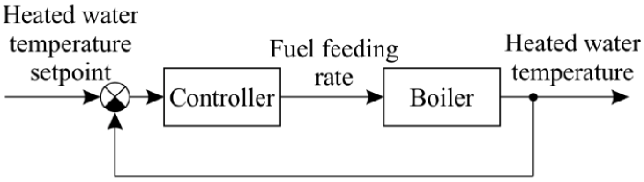

Fig. 8 Control circuit block scheme of the heated water temperature control

As the target temperature has been selected the level of 70 °C. At certain time, it has been introduced a disturbance evoked by a sudden change of heat demand. This disturbance has been simulated by increase of the water flow through the boiler while the temperature set point has remained constant. Results of the PI control are shown by the courses in Fig. 9.

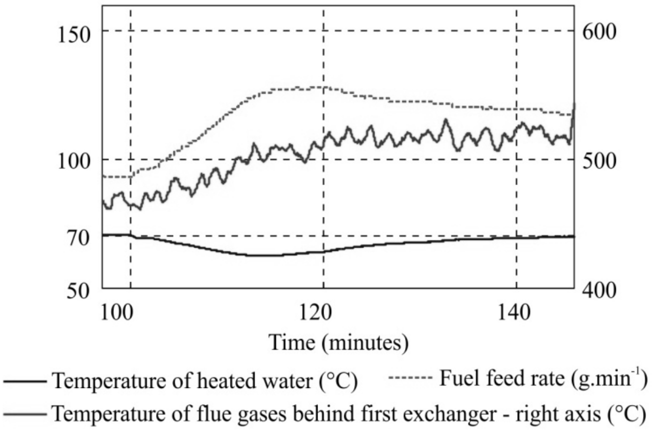

Fig. 9 Operation of the PI controller

The disturbance has been introduced in the time instant 100 min from the beginning of the experiment. The controller smoothly reacts by increase of the fuel feeding rate to compensate the temperature drop. It can be seen also significantly decreased variations of the T2 temperature down to between 10 °C and 20 °C.

VIII. Advantage of the Continuous Control – Fuel Saving

Generally, it has been previously shown that the continuous control significantly improves stability of the boiler's operation. By further experiments, it has been shown that this is also reflected in a lowered consumption of fuel related to 1 MJ of the produced heat, i.e. the continuous control helps to improve efficiency of the boiler.

The experiments have been run with both original on-off control unit and PI continuous controller. The conditions were similar to the case described in Chapter VI. For both situations, two disturbances have been introduced by means of change of the power output of the boiler, using change in the water flow through the boiler and keeping the same set point for the water temperature. Operation of the original on-off controller is shown in Fig. 10. In the figure, the temperature of the outlet water (thick line) is shown having the set point at 90 °C. The feeding rate (thin line) is also shown there together with the calculated average fuel consumption in grams of fuel per 1 MJ of produced heat (dotted line). This consumption is calculated as average between two introduced disturbances. Even if in the depicting different set points of the heating water temperature for both cases have been used, the results are comparable, because the resulting power output has been maintained at the same level.

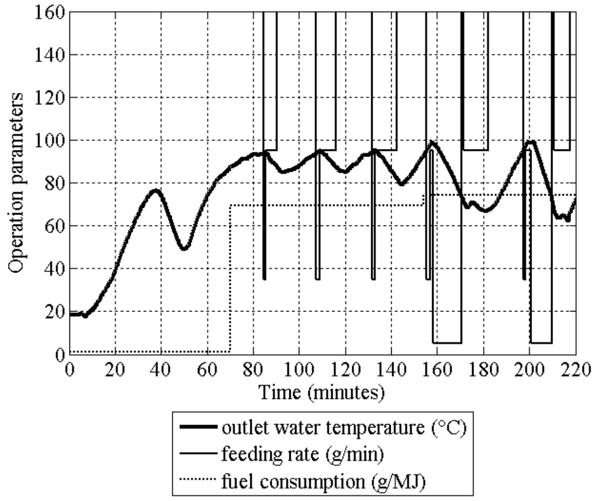

Fig. 10 Operation boiler data with evaluation of the fuel consumption if an on-off controller was used for temperature control

The calculated fuel consumptions are 73 and 69 g/MJ respectively. Following Fig. 11 shows the same situation when the PI controller has been used. The outlet water temperature set point was 70 °C as for the case in Chapter VI. Patterns of the lines have the same meaning as for Fig. 10. The calculated fuel consumptions for this case are 58, 64, and 53 g/MJ, respectively. We can clearly see improvement in the fuel consumption that has decreased in average by approximately 17 %, which is very important for economy of the boiler's operation.

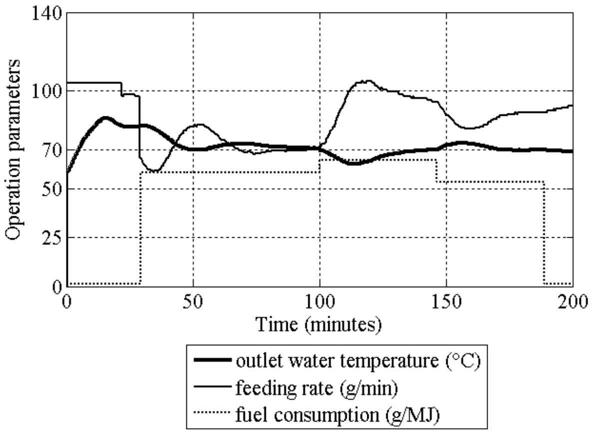

Fig. 11 Operation boiler data with evaluation of the fuel consumption if a PI controller was used for temperature control

There have been also evaluated mean values, maximum and minimum values and standard deviations across the whole length of the experiments of carbon monoxide concentration, temperature of outlet water and temperature T2. The evaluated values for the on-off control are shown in Table 1 and for the PI controller in Table 2.

Table 1: Evaluation of the operation data for on-off control

	Avg	Max	Min	St.dev.
CO (ppm)	306	3007	13	553,5
TWout (°C)	76	99	61	20,4
T2 (°C)	526	686	415	154,5

Table 2: Evaluation of the operation data for PI control

	Avg	Max	Min	St.dev.
CO (ppm)	75	1324	10	146,6
TWout (°C)	72	86	65	5,3
T2 (°C)	508	569	485	32,7

Comparing the values from Tables 1 and 2 it can be clearly seen effect of the PI control. From the emissions point of view, as the reference flue gas component has been selected carbon monoxide, which is a typical product of incomplete (and therefore less efficient) combustion. Average CO value for the case of the PI control is approximately four times lower compared to the on-off control. Also the stability of the CO level is much better for the PI controller, looking on the standard deviation values.

The effect of the PI controller can be also well seen in stability of temperature of the outlet water. The set point 70 °C was very well kept at the desired value with standard deviation 5,3 °C. Stability of the combustion process itself has also improved, which is identified here by the T2 temperature (flue gas temperature after the first heat exchanging section).

IX. CONCLUSIONS

The main aim of this paper was to show important ecological tasks ensured by the control systems of the small-scale biomass boilers. There is generally not much to improve in construction of the combustion chambers of the boilers, because there has been strong development during last years towards emissions. But there is still lot to improve in the control systems. In the paper, it has been proposed a solution based on exchange of the currently used simple on-off control unit by advanced control solutions using PAC with the restriction not to increase cost of the boiler significantly. For this purpose, the experimental boiler has been equipped by additional instrumentation with extended functions, which can be later incorporated into commercially available units for the small biomass boilers, keeping all the advanced functions that have been developed. It has been shown optimized solution for the grate sweeping that originally caused increased peaks in CO and hydrocarbons emissions that need to be reduced to fulfill requirements for an ecological operation of the boiler. Use of the advanced control allows modification of travel distance of the grate moving mechanism and therefore sweeping the grate without causing serious disturbances in the process.

The other control task for the ecological operation of the boiler is detection of possible malfunction of the lambda-probe, which is essential for sustaining operation of the boiler at low emissions and high efficiency. The situation has been shown on two-loop control algorithm that has been created for the biomass boiler. On the step changes of combustion airflow has been shown reaction of the CO emissions of the boiler. Based on this, it has been shown on one step change of the lambda-probe property reaction of the temperature and oxygen control loops, causing the process to be out of the optimal working range of the excess air ratio. Based on this process identification, there has been proposed solution of malfunction detection based on comparison of response of the developed model of the sensor and response of the real lambda-probe.

Another aspect of the small-scale pellet boiler operation is fuel consumption. It has been proposed and programmed use of a PI controller for sustaining the set point of the outlet water temperature by changing the fuel feeding rate. Carried out experiments comparing behavior of the original on-off regulation and newly introduced PI control with the aim to evaluate fuel consumption and consequently efficiency, calculated as grams of consumed fuel per MJ of produced heat transferred into the heating water. It has been shown that at similar conditions (the same heat power output) the operation controlled by the PI controller consumes less fuel than for the case with on-off control. The difference has been for this case found approximately 17 %.

The future work in this field will be focused on further improvement in optimization of the enhanced control and implementation of the proposed model of the behavior of the lambda-probe into the control algorithms.

Significant benefit of the PI controller is improved stability of the outlet water temperature. The PI controller also significantly improved CO emissions from the combustion process, compared to the on-off control. Furthermore, stability of the combustion process has been improved which is identified by the temperature after the first heat exchanger

The future work in this field will be focused on further improvement in optimization of the continuous control and implementation of the proposed model of the behavior of the lambda-probe into the control algorithms.

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