A new burnout control strategy for small-scale biomass furnaces based on the continuous estimation of the CO-O_2-characteristic

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Abstract

This paper presents a control strategy for small-scale biomass furnaces based on the oxygen and carbon monoxide concentration in the flue gas. A Kalman filter is used to continuously estimate the correlation between the oxygen concentration and the resulting carbon monoxide emissions (well-known as the CO-λ-characteristic). A subordinate oxygen controller regulates the oxygen concentration to the estimated emission-optimal value. Experimental results from a commercially available small-scale wood-chip furnace demonstrate that the combustion can be enhanced by the new control system. Especially under difficult conditions, as for example drifting oxygen sensors, changing fuel moisture contents or varying load demands, significant improvements can be achieved. It is shown that the control strategy presented, based on the combined measurement of carbon monoxide and oxygen concentration, leads to a significant reduction of CO emissions and lower excess air ratios.

Keywords: combustion control, carbon monoxide based control, wood chip combustion, emission reduction, Kalman filter for parameter estimation

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1. Introduction

During the last years, biomass combustion for residential heating and warm water production became more popular for a number of reasons. Among those are different government subsidy programs to increase the share of renewable and CO_2 neutral energy systems, but also developments in automatic feeding systems leading to a strong increase of convenience and performance of furnaces, contributing to an increasing number of biomass furnaces. Field measurements of small-scale biomass furnaces for residential heating show much higher emissions and lower efficiencies than deduced from standardized tests [1, 2, 3, 4]. This is mainly due to highly optimized steady state conditions and high quality fuels, that are used for these measurements on the test bench. For example, in [3] it is demonstrated that the measured CO emissions for the same furnace are up to 15 times higher in practical applications (chimney sweeper measurements) than in standardized tests. In practice, the biomass furnace has to handle many unknown influencing factors such as changing fuel qualities, varying load demands, ageing (e.g. sensor drift) and improper handling by the operator. Therefore, modern biomass furnaces are operated at conservatively (high) air ratios to compensate for these unknown factors and guaranty a sufficient gas phase burnout. Mostly, this leads to decreased efficiencies and higher emissions.

However, the O_2 concentration is only an indirect indicator for the burnout quality. There are no universally valid relations between the O_2 content of the flue gas and the amount of resulting emissions for different biomass furnaces. As already mentioned, it can be very challenging to determine the actual optimal settings for the O_2 set point $c_{O_2,s}$, because many different factors influence the dependency between the completeness of the combustion and the excess air ratio. A much better and often-used indicator for the combustion quality is the level of carbon monoxide in the flue gas. CO is generally known as a good tracer for the overall combustion quality and correlates with the most important pollutants of the biomass combustion (HC, PAHs, quantitatively even with particles). Nevertheless, usage of the oxygen concentration is more suitable to stabilize the combustion than only the CO concentration. This suggests to use the CO concentration together with the O_2 concentration as measure for the combustion quality and to use both concentrations for controlling the combustion process.

Recent developments in robust and low-cost carbon monoxide sensors (e.g. [5, 6, 7]) result in new control strategies becoming economically interesting. It can be assumed that these sensor become affordable in the next years even for small and medium scale heating systems.

Thus, new control systems, based on the measurement of the CO concentration, can principally make a valuable contribution towards compensating for the deficits of current oxygen based control strategies [8]. They allow to operate the biomass furnace closer to the optimal operating point regarding the emissions.

This paper will present a strategy for burnout control, which estimates continuously the CO-O_2-characteristic to determine an emission-optimal excess air ratio and thus to minimize the emissions.

The paper is divided in the introduction (section 1), followed by a description of the state of the art of control systems currently applied (section 2), literature review on existing CO-O_2-controllers (section 3), an explanation of the new method developed (section 4) and decription of the experiment setup (section 5). Subsequently, the results of the experimental validation for different operating conditions and frequently encountered disturbances are presented (section 6). Load variations (subsection 6.1), artificial sensor drift (subsection 6.2) and changing fuel moisture content (subsection 6.3) are investigated. Finally, a short summary and conclusion are given (section 7).

2. State of the art: oxygen based burnout control

Currently, the burnout of modern small-scale biomass furnaces[1] is usually controlled by the signal of a lambda probe, e.g. [12, 13]. Figure 1 illustrates the typically used control loop with a PID controller and a lambda probe. The manufacturers of the firing systems choose an oxygen set point $c_{O_2,s}$ (typically between 5-10 vol% w.b.). Mostly, a simple linear controller (e.g. standard PID-controller) is used for compensating disturbances and drifts. The oxygen concentration c_{O_2} measured by the lambda probe is compared to a set point $c_{O_2,s}$, and the controller varies the manipulated variable u (typically the secondary fan power) to control the oxgen concentration c_{O_2}. This control loop can be easily adjusted and the available lambda probes and PID-controllers are technically mature. Examples of applications can be found in [14, 15, 16]. But also recent developments in model based controllers [17, 18, 19] have shown their potential for small-scale biomass furnaces.

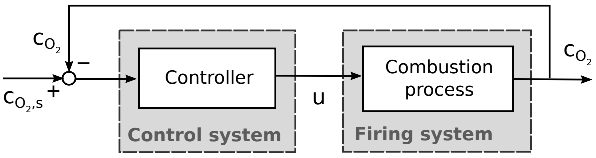

Figure 1: Commonly used control system for burnout control based on a lambda probe. Maniplated variables u, oxygen concentration c_{O_2} measured by the lambda probe and desired set point of oxygen concentration $c_{O_2,s}$ are shown.

However, these oxygen-based control strategies involve a crucial drawback: the predetermined and constant set point $c_{O_2,s}$ for the oxygen concentration. To determine the actual optimal oxygen set point $c_{O_2,s}$ can be very challenging, because the optimal oxygen concentration is influenced by many different (mostly unknown) factors. Several works, e.g. [15, 20, 21], have shown that for example the current thermal output [15] or the flue gas recirculation rate as well as the fuel moisture content [20, 21] strongly influence the optimal air-fuel ratio λ. Also leakage air and age-related sensor offsets have a strong influence on the optimal set point for the oxygen concentration. This strongly suggests to optimize the oxygen set point in real-time during the combustion process.

3. Literature review: carbon monoxide and oxygen based burnout control

In this paper, this class of combustion controller, which use a CO sensor and a lambda probe, will be called CO-O_2-control even if CO-λ-control is the more often used term. This is because the term CO-O_2-control decribes the basic principle of the developed control more appropriate. The term CO-O_2clarifies the fact that this class of controller optimizes the oxygen concentration (on wet basis) and only indirectly influences the air-fuel ratio λ.

Several works, e.g. [12, 22], present approaches to control furnaces by the carbon monoxide concentration c_{CO} in the flue gas. The concepts are quite simple: The averaged CO concentrations for two different oxygen set points are compared and the new set point $c_{O_2,s}$ is moved after a fixed time interval in the direction of the gradient similar to the method of gradient descent. These class of algorithms tries to determine some kind of local gradient of the CO-O_2-characteristic and minimize the emissions by moving in the direction of ex-

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[1] as well as most combustion processes (e.g fluidized bed [9] furnace, diesel engines [10, 11], SI engines and others.)

pected lower emissions. Implementations of these algorithms have shown that long averaging intervals are necessary to filter stochastic fluctuations of the CO concentration and thereby to be able to compare the emissions before and after a change of the oxygen concentration. This implies that long time intervals are necessary to calculate a reliable gradient and to find the optimal oxygen concentration. Additionally, these concepts are only successfully validated for steady state conditions.

Good and Nussbaumer presented in [15, 23, 24] another approach for a CO-O_2-controller. The oxygen concentration is divided into a grid of ranges. The measured CO concentration at a specific oxygen concentration is averaged with all the previous CO-values in the current oxygen range. Finally, the oxygen range with the lowest emissions is chosen as the new set point.

The main disadvantage of this relatively simple algorithm is the fact that stochastic variation of the CO concentration (which always exists) can either lead to a wrong set point or to long averaging intervals. Moreover, a too fine chosen grid increases the time to find the optimal oxygen concentration, because a certain number of values have to be collected to get reliable means for every range. On the other hand, a too coarse grid leads to a poor estimation of the optimal oxygen concentration, because the estimation can only be as precise as the step size of the grid.

4. Main principle of the new control strategy

The new strategy presented within this paper overcomes the disadvantages of previous works, by estimating the characteristic itself instead of estimating the gradient at a specific point of the CO-O_2-characteristic. Additionally, there is no need of dividing the oxygen concentration in a grid and averaging the available measurements. As we will show in the experimental validation, the new concept leads to a fast convergence to the optimal oxygen concentration. Furthermore, short-term changes of the combustion condition can be recognized and the set point can be adapted accordingly.
The system can be divided into three main components: the control system, the furnace itself and finally the CO-O_2-estimator of the CO-O_2-characteristic. Figure 2 illustrates the structure of the entire system. To control the oxygen concentration, the current oxygen concentration c_{O_2} is compared to the desired set point $c_{O_2,s}$. The difference (control error e_{O_2}) is used by the controller to calculate – depending on the control method applied – the manipulated variable(s) u. For simple control circuits, the manipulated variable u is mostly the fan power of the secondary air fan. More complex control systems, based on a multivariable controller, which calculates several manipulated variables u simultaneously (e.g. primary mass flow, secondary mass flow and fuel mass flow [25, 26]).

The manipulated variables influence the oxygen concentration c_{O_2} and thereby – depending on the CO-λ-characteristic – the carbon monoxide concentration. The main idea of the new control strategy is to estimate the time-variant CO-O_2-characteristic by a Kalman filter. This is done by assuming that the CO-O_2-characteristic can be locally approximated by a parabola

$$c_{CO} = x_1 \cdot c_{O_2}^2 + x_2 \cdot c_{O_2} + x_3. \qquad (1)$$

A standard discrete Kalman filter (introductory literature can be for example found in [27, 28]) continuously estimates the model parameter $x = \begin{bmatrix} x_1, x_2, x_3 \end{bmatrix}^T$ of the parabola. Expressed in simplified terms, the Kalman filter fits the parabola to the previously measured CO and O_2 concentrations, whereby new measurements are weighted stronger. If a good estimate of the characteristic is achieved (typically after 2-4 min), the emission-optimal oxygen concentration $c_{O_2,opt}$ can be predicted by calculating the minimum of the parabola. This is done by zeroing the first derivative of the parabola. This predicted minimum is a quite good estimate for the current optimal oxygen concentration. The prediction continuously improves by new measurements of O_2 and CO. In order to avoid fast fluctuations of the operating point, a standard low pass filter is used to smooth the predicted optimal concentration $c_{O_2,opt}$. This newly calculated optimal oxygen concentration is finally used as the new set point for the oxygen controller. These steps will be repeated in fixed time interval (e.g. every second), and the set point as well as the actual oxygen concentration converge towards the optimal O_2 concentration over time.

5. Setup and methodology for experimental validation

A commercially available wood-chip boiler with a nominal boiler capacity of 30 kW was used for the experimental validation. Figure 3 shows the schematic plant layout. Two fans (1+2) are used to set the primary and secondary air mass flows. The fuel is supplied by the feed screwer (3) onto a moving grate (4). The fuel bed is shown in (6). The secondary combustion chamber is water cooled (5). The flue gas fan (10) is used to ensure a negative pressure in the combustion chamber. For estimation of the CO-O_2-characteristic, a combination probe (KS1D of Lamtec) is used. The

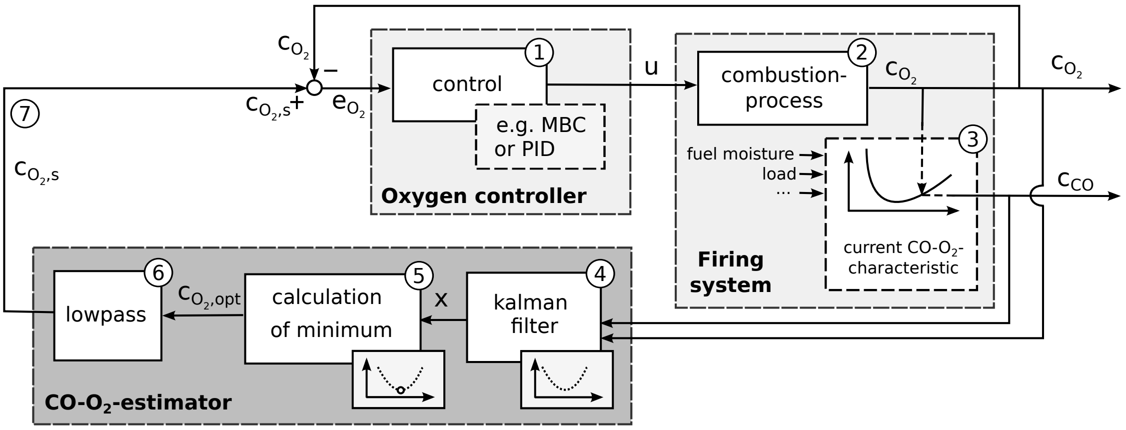

Figure 2: Main scheme of the newly proposed control system. (1) A standard O_2-controller controls the oxygen concentration c_{O_2} to the desired set point $c_{O_2,s}$ by influencing the manipulated variables u (e.g. secondary fan). The manipulated variables u influence the combustion process (2) and consequently the oxygen concentration c_{O_2}. This results in a certain CO-concentration c_{CO} depending on the current combustion condition and the current CO-O_2-characteristic (3). The kalman filter (4) estimates the parameters x of a mathematical decription of the CO-O_2-characteristic. The minimum of the estimated function is calculated (5) and is used after filtering (6) as the new optimal oxygen set point (7).

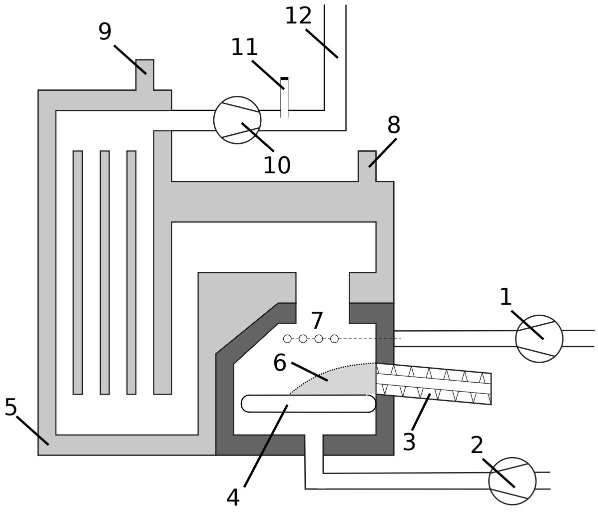

Figure 3: Main scheme of the wood chip furnace. (1) fan for secondary air, (2) fan for primary air, (3) fuel screwer, (4) travelling grate, (5) furnace, (6) firebed, (7) secondary air nozzles, (8) hydraulic connection (feed), (9) hydraulic connection (return), (10) flue gas fan, (11) KS1D sensor to measure CO and O_2 (12) chimney.

combination probe, which is placed downstream the flue gas fan (11), is able to simultaneously measure the oxygen concentration and the sum of oxidisable components (so called COe – carbon monoxide equivalent [29]). The COe-signal of the KS1D not only depends on the CO concentration, but also on all other combustible components, e.g. H_2. Additionally, the combination probe has a correlation to the oxygen concentration, but it has been shown that empirical models can compensate this interference sufficiently well [22]. Nevertheless, typical relative errors of the CO concentration have to be expected in the range of approximately 30 %. It should also be emphasized that the control algorithm presented is highly robust to offsets and wrong magnitudes of the measurement data used. A correct detection of the general tendencies of the combustion quality is already sufficient for a suitable estimation of the CO-O_2-characteristic, since only the position of its minimum is relevant. A flue gas analyzer (Rosemount – NGA 2000) was used as a reference for the oxygen and carbon monoxide concentrations. These concentrations are related to standard reference conditions for gases (pressure: 101.325 kPa, temperature: 273.15 K) and measured on dry basis is used. Within this paper all values measured by the flue gas analyzer are indicated by the index *FGA*, whereas concentrations without an index are measured by the KS1D probe. All CO concentration are related to 13 vol% d.b.

The furnace was principally developed for moisture contents up to 30 wt% w.b. However, most of the experiments have been performed with a fuel moisture content of above 30 wt% w.b. This leads to higher emissions, but demonstrates the full potential of the new control system particularly for difficult combustion conditions.

First, the behaviour of the controller (model based control – MBC) at changing load demands was investigated. Strongly simplified, this model based controller influences the primary and secondary air mass flow, as well as the fuel mass flow, to regulate the feed temperature and the oxygen concentration. It also takes the coupling between the different physical values into account. A detailed description of the model and the controller itself can be found in [25, 26]. The load variations have been performed with and without the CO-O_2-estimator. The corresponding experimental results are shown in section 6.1.

Secondly, an artificial drift of the lambda-probe was simulated. Again, the results with and without the CO-O_2-estimator have been compared (6.2). For this experiment, the plant again was operated by the model based control.

Finally, several changes of the fuel moisture have been performed, but only with the CO-O_2-estimator. The experimental results are discussed in subsection 6.3. To demonstrate the modularity, this experiment has been performed with simple PID-controllers. Thereby the oxygen concentration was mainly controlled by the fan power of the secondary air and the feed temperature was controlled by the fuel mass flow.

6. Results and Discussion

6.1. Load variations

In practical applications, biomass heating systems are always operated at varying load demands. To validate the control system for changing loads, a predefined load cycle was used.

For this, wood chips with a fuel moisture content of approximately 35 wt% w.b. were used and the desired set point of the feed temperature was set to 73 °C. The load cycle started at nearly nominal load (28 kW) (warm start) and changed after 1 h within 0.5 h to the minimal load (11 kW). After another hour, the load is increased to partial load with 19 kW within 0.25 h.

For validation the advanced model based oxygen controller was used. Figure 4 shows the feed temperature T_F and return temperature T_R as well as the the set point for the temperatures. The controller was able to hold the feed temperature (standard deviation is 0.46 °C) even for changing loads at the desired set point.

For the operation without the new CO-O_2-estimator, appropriate set points of the oxygen concentration were determined for nominal and partial load by previous experiments. The set points are linearly interpolated for loads between nominal and partial load. Figure 5 illustrates the oxygen set points for different loads.

Figures 6 and 7 illustrate the oxygen concentrations (actual oxygen value c_{O_2}, the set points $c_{O_2,s}$ and averaged values of c_{O_2}) for the controller with and without CO-O_2-estimator .

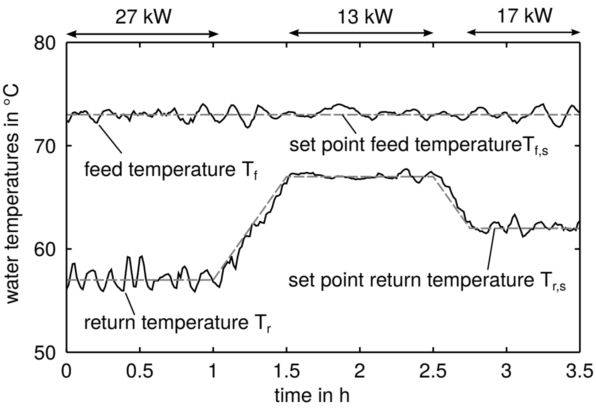

Figure 4: Feed and return temperatures for the MBC controller with activated CO-O_2-estimator (the temperatures for the MBC controller without CO-O_2-estimator are quite similar).

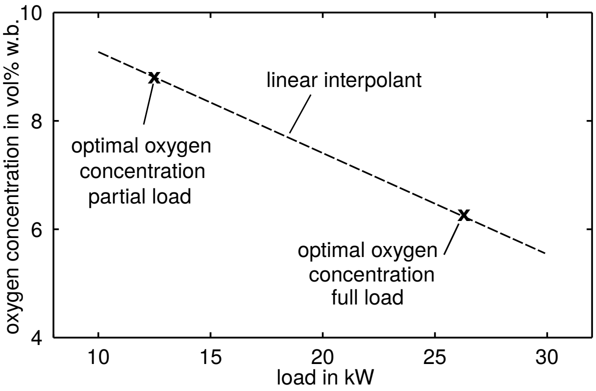

Figure 5: Set points for the oxygen concentration at different loads (interpolated between the two optimal set points for full load and partial load).

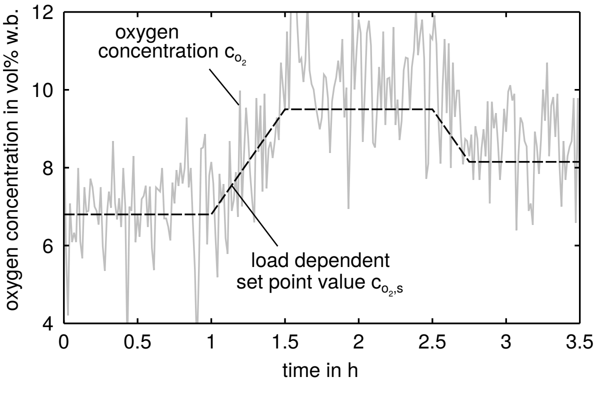

Figure 6: Oxygen concentration c_{O_2} and predefined set point $c_{O_2,s}$ (load-dependend) over time for the experiment without CO-O_2-estimator.

As shown in Figure 5 and 6, a higher load (first third of the experiment) allows for lower oxygen concentration ($c_{O_2,s} \approx 6.8$ vol% for 28 kW), whereas at partial load a certain secondary air mass flow¡ is required to achieve a sufficient mixing ($c_{O_2,s} \approx 9.8$ vol% for 11 kW).

Figure 7 illustrates the oxygen concentrations (actual oxygen value c_{O_2}, the set points $c_{O_2,s}$ and averaged values of c_{O_2}) for the controller with CO-O$_2$-estimator.

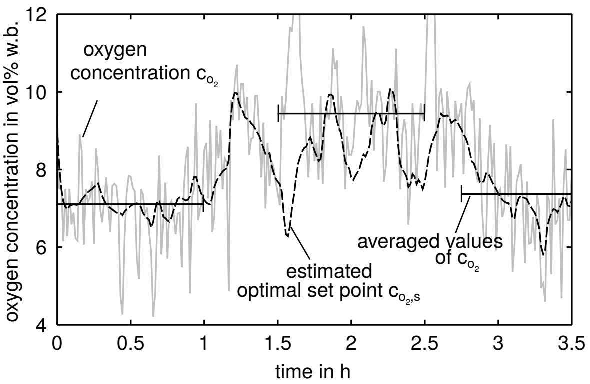

Figure 7: Oxygen concentration c_{O_2}, estimated optimal concentration $c_{O_2,s}$ and averaged oxygen concentration over time for experiment with CO-O$_2$-estimator.

In contrast to the experiment without the CO-O$_2$-estimator, the CO-O$_2$-estimator finds for every load the optimal oxygen concentration and sets the set point of the oxygen concentration to the estimated optimum. As shown in Figure 7, the general profile of the set point looks similar to the predefined one of the experiment without the CO-O$_2$-estimator. For full load, an optimal oxygen concentration is estimated around 7.2 vol% w.b. In partial load the prediction fluctuates stronger because the combustion itself is more unstable but the general O$_2$ profil has a quite similar shape to the predefined set points of the experiment without the CO-O$_2$-estimator. Interestingly, the estimated optimal oxygen concentration for upper partial load (19 kW) is very close to the values of nominal load. This implies that a simple linear interpolation of the set points, as done for the experiments without the CO-O$_2$-estimator, is not sufficient. Finally, this demonstrates how difficult it is to determine the optimal oxygen concentration a priori.

The main results for the two controllers are summarized in Table 1. The results show that there is only a slight difference in the standard deviations (1.12 vol% d.b. without the CO-O$_2$-estimator and 1.35 vol% d.b. with the CO-O$_2$-estimator), which is caused by stochastic fluctuations. The CO-O$_2$-estimator achieved a 27 % decrease of the averaged CO emissions in comparison to the controller without the CO-O$_2$-estimator. The controller with the CO-O$_2$-estimator decreased the averaged oxygen concentration over the entire experiment by 0.4 vol% d.b. correlating with an efficiency increase. In summary, this experiment has shown that the CO-O$_2$-estimator leads to lower CO concentrations in the entire load range as well as lower excess air ratios. Even for manually optimized oxygen set points (for different loads), on the basis of specific previous experiments, the CO emissions have been higher than with the new CO-O$_2$-estimator.

6.2. *Artificial sensor offset*

In practical applications, the λ-probe is permanently exposed to the rough conditions in the flue gas. High temperatures, acid condensates, ash and dust deposits and finally the high number of operating hours of the furnace lead to decreased sensitivities and offset drifts of the oxygen sensor[2]. Additionally, the accuracy of the oxygen measurement is negatively influenced by an interference of the lambda probe to carbon monoxide. Finally the excess air ratio is influenced by changes of flue gas moisture content, becauce always the oxygen concentration on wet basis (lambda probe) is controlled. In the following experiment, the behaviour (model based control) with and without the CO-O$_2$-estimator under the influence of an artificial sensor offset of the λ-probe is investigated. The experiment starts with an offset of 0 vol%. After 0.5 h the sensor offset is continuously decreased to -3 vol% w.b. within 1 h. After another 0.5 h the sensor offset is reset to zero within 5 min. Figure 8 shows the implemented sensor offset over the experiment time. Direct drifts of the CO sensor signal are not considered in this experiment, but indirectly the CO level is influenced by normalization with the drifted O$_2$ concentration. The experiment has been performed at a load of 16 kW and wood chips with a fuel moisture content of 35 wt% w.b. were used. Figure 9 shows the

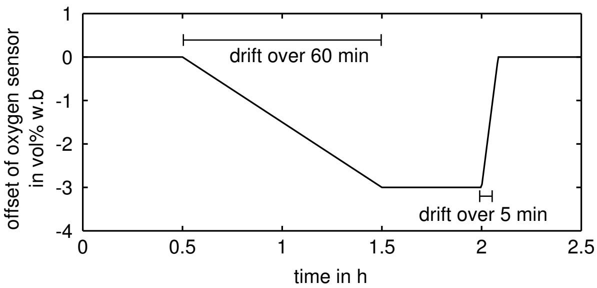

Figure 8: Artificial drift of the λ-probe over time.

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[2] To compensate these effects, some manufactures of biomass furnaces try to correct the sensor output by roughly estimated age-related factors, e.g. [30].

Variable		Unit	without CO-O$_2$	with CO-O$_2$
$c_{O_2,FGA}$	mean for EE	vol% d.b.	8.6	8.2
	mean for NL$_{27\,kW}$	vol% d.b.	6.9	7.1
	mean for PL$_{19\,kW}$	vol% d.b.	8.6	7.3
	mean for PL$_{11\,kW}$	vol% d.b.	10.3	9.4
$c_{CO,FGA}$	mean for EE	mg m^{-3} d.b.	507	369
	mean for NL$_{27\,kW}$	mg m^{-3} d.b.	205	89
	mean for PL$_{19\,kW}$	mg m^{-3} d.b.	332	248
	mean for PL$_{11\,kW}$	mg m^{-3} d.b.	929	751
w_{H_2O}		wt% w.b.	35.8	35.6

Table 1: Results for load cycles with and without the CO-O$_2$-estimator. The mean values over the entire experiment (EE), over the interval of nominal load (NL$_{27\,kW}$), over the interval of partial load with 19 kW (PL$_{19\,kW}$) and over the interval of partial load with 11 kW (PL$_{11\,kW}$) are separately shown.

O$_2$ and CO concentration for the experiment without the CO-O$_2$estimator. As expected, the actual oxygen concentration measured by the flue gas analyzer and the sensor signal of the KS1D (which was used for the control) goes along in the first 0.5 h. Slight differences only exist due to the different basis (KS1D on wet basis and FGA on dry basis). After the first 0.5 h, the KS1D sensor starts (artificially) to drift. Without an oxygen controller the O$_2$ concentration of the lambda probe c_{O_2} would decrease because of the drift. But in the experiment, the oxygen controller holds the (*drifted*) oxygen concentration to the set point of 10.5 vol% w.b by increasing the secondary air mass flow, whereby the (*actual*) oxygen concentration $c_{O_2,FGA}$ measured by the flue gas analyzer increases. The fixed set point $c_{O_2,s}$ 10.5 vol% w.b. of the oxygen controller is also shown (black dashed line). After 1 h, the stationary offset of -3 vol% w.b is reached and an offset of approximately 3 vol% w.b between FGA and lambda probe exists. As expected, the high *actual* oxygen concentration leads to a decrease of the burnout quality. The CO-emissions (shown in the lower graph of Figure 9) increased up to an averaged level of 5211 mg m^{-3}.

For comparison, Figure 10 illustrates the results with the activated CO-O$_2$-estimator. As shown in Figure 10, the average value of the actual oxygen concentration (FGA) stays nearly constant, even if the sensor signal of the KS1D sensor has an offset of -3 vol% w.b. oxygen. The low level of CO concentrations with the activated CO-O$_2$-estimator clearly demonstrates the advantage of the CO-O$_2$-estimator. Whereas the CO emissions stay nearly constant for the activated CO-O$_2$-estimator, a normal oxygen based control strategy leads to a strong increase of CO concentration. Over the entire experiment the CO emissions c_{CO} could be decrease by 81 % (without the CO-O$_2$-estimator : 2292 mg m^{-3} d.b. and with the CO-O$_2$-estimator : 439 mg m^{-3} d.b.) through the CO-O$_2$-estimator. Again, the standard deviation of the oxygen concentration with and without the CO-O$_2$-estimator are comparable (with the CO-O$_2$-estimator : 1.68 vol% w.b. and without the CO-O$_2$-estimator : 1.43 vol% w.b.). Table 2 summarizes the results for both experiments (with and without the CO-O$_2$-estimator).

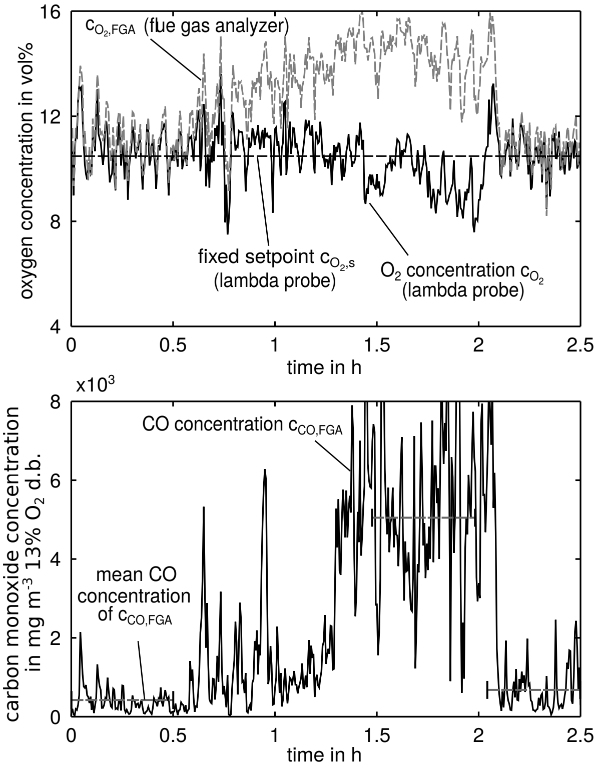

Figure 9: Oxygen (top) and carbon monoxide concentration (bottom) for the experiment with artificial sensor drift and without the CO-O$_2$-estimator.

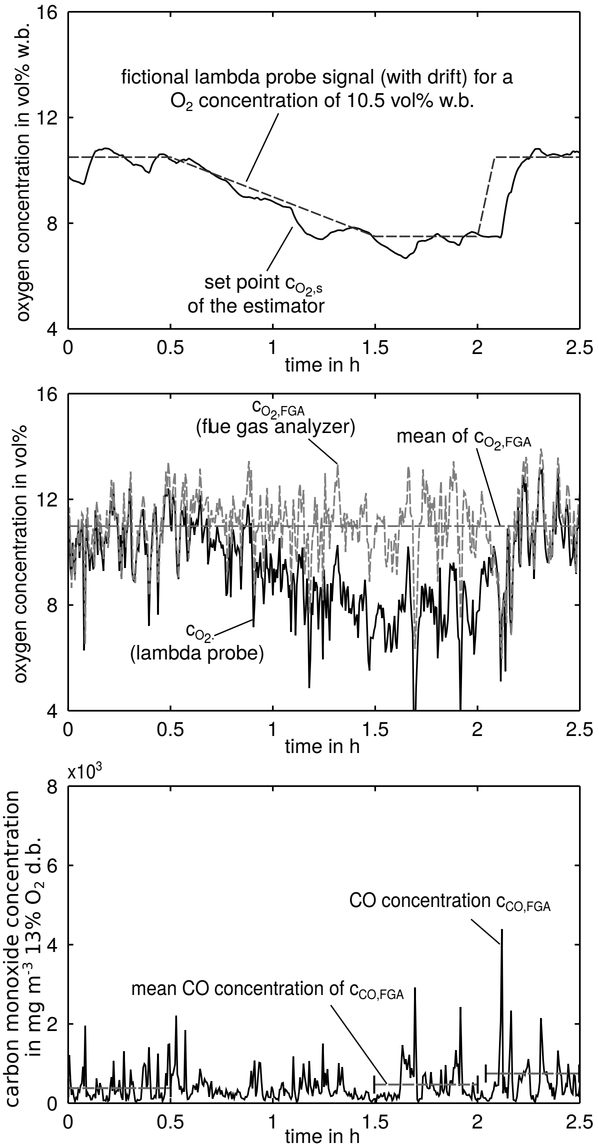

Figure 10: Oxygen (top and middle) and carbon monoxide concentration (bottom) for the experiment with the CO-O_2-estimator and artificial sensor drift.

Variable		Unit	with	without
c_{O_2}	mean	vol% w.b.	10.6	11.7
$c_{CO,FGA}$	mean	$mg\,m^{-3}$ d.b.	439	2292
$\dot{Q}$	mean	kW	16.1	16.1
w_{H_2O}		wt% w.b.	35.3*	35.3*

Table 2: Results for sensor drift (*same fuel for the experiment with and without the CO-O_2-estimator).

In summary, this experiment has shown that a sensor offset of the lambda probe can be compensated by the CO-O_2-estimator and that the CO-O_2-estimator is able to hold the optimal oxygen concentration even for drifting sensor signals. The new CO-O_2-estimator thus would lead to a reduction of the maintenance effort in practical applications because even high sensor offsets of the lambda probe could be fully compensated.

6.3. Change of the fuel moisture content

Several studies have shown (e.g. [20, 21, 15]) that the optimal excess air ratio is influenced by the fuel moisture content. Higher fuel moisture contents decrease the adiabatic combustion temperature and consequently influence the shape of the CO-λ-characteristic. In addition to the deformation of the CO-O_2-charcteristic, the CO-O_2 characteristic (related to wet basis) is shifted by the resulting dilution with water vapour (depending on the fuel moisture content). For district heating plants or combined heat and power plants the optimal excess air ratio can be manually adapted to the measured or estimated fuel moisture content. In small-scale wood chip applications, there is no direct information about the current fuel moisture content available, and a constant set point for the excess air ratio has to be chosen. It is obvious that these constant set points can lead to higher emissions and decreased efficiencies when the fuel moisture content changes. For this reason, within the experiment decribed next the CO-O_2-estimator was validated with step-wise changes of the moisture content of the fuel. Additionally, the following experiment was performed with a very simple PID-based oxygen controller in contrast to the previous described experiments for which the advanced model based control strategy was applied. Thus, with this experiment, both the ability to compensate changes of the CO-O_2-characteristic related to the fuel properties as well as the ability to cooperate with different control systems can be validated.

The entire experiment has been performed at a constant load (25 kW) with a total duration of the experiment of 4 h. After one hour, the fuel moisture content was changed from approximately 38 wt% w.b. to 18 wt% w.b. After another two hours the moisture content was increased to a moisture content of 44 wt% w.b.

Figure 11 shows the estimated optimal set points for the oxygen concentration. For the operation with 38 wt% w.b. (first hour) the optimal oxygen concentration varied between 7 vol% and 8 vol%, which is within the range of normal oxygen fluctuation (typical standard deviation of the PID is around 1.1 vol% w.b.). For the operation at 18 wt% w.b. moisture content of the fuel, the estimation of the optimal set point strongly converged towards approximately 8.2 vol% and thereby

0.7 vol% higher than for the operation with a moisture content of 38 wt% w.b.. Two main superimposed effects can explain this. First, a higher fuel moisture content leads to a stronger dilution of flue gas with water vapour, which shifts the (wet) CO-O_2-characteristic to lower oxygen concentrations. Second, the lower adiabatic flame temperature increases the sensitivity of the combustion to additional temperature reductions caused by high excess air ratios. The corresponding CO concentration are shown in Figure 12. As expected, the CO concentration is much lower for dry fuel (average for 18 wt% w.b.: 72 mg m^{-3} d.b.) compared to wet fuel (average for 45 wt% w.b. : 793 mg m^{-3} d.b. and average for 38 wt% w.b.: 435 mg m^{-3} d.b). In summary, this experiment has shown that the CO-O_2-estimator is able to adapt the oxygen set point to the current moisture content very well. Additionally, this experiment has also proven that the CO-O_2-estimator develloped can be combined with different oxygen controllers.

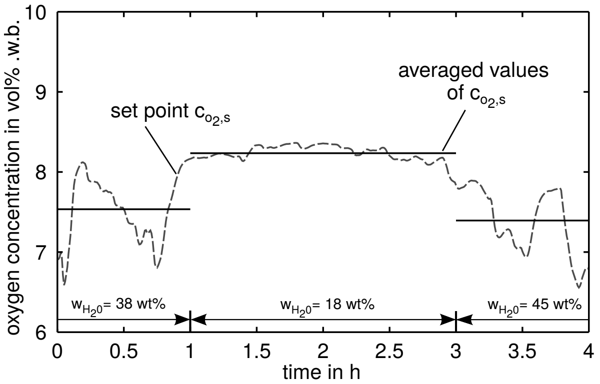

Figure 11: Oxygen concentration for the experiment with changing fuel moisture content. The CO-O_2-estimator estimates different oxygen set points for different fuel moisture contents.

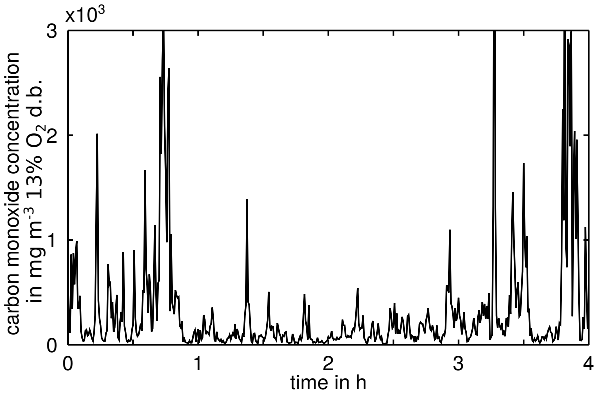

Figure 12: Carbon monoxide concentrations for different fuel moisture contents.

7. Summary and Conclusion

A new control strategy to find the emission-optimal oxygen concentration during the combustion by approximating the CO-O_2-characteristic has been presented. The main principle has been illustrated and the main components have been explained. Subsequently, the new strategy has been verified at a commercially available small-scale biomass boiler at different practically relevant operating conditions typically causing emission increases as well as eficiency lossed. The control system developed is able to compensate different changes of the CO-O_2-characteristic, independent wether they are caused by a drift of the lambda probe, a load change or a change of the moisture content of the fuel. In particular, for the experiments with load variations, the CO-O_2-estimator reduced the oxygen concentration by 0.4 vol% d.b. and the carbon monoxide concentration by 27 % on average. Also, for the experiments with a drifting λ-probe, a considerable reduction have been achieved (O_2 decreased by 1.1 vol% d.b. and CO reduced by 81 %). Changing fuel moisture contents have been detected very well and the set point of the oxygen concentration has been adapted appropriately. Furthermore, the new concept proved its modularity by implementing the concept in combination with two different controllers, a simple PID controller as well as an advanced model based control strategy.

In summary, the results presented in this paper have shown that the new CO-O_2-estimator based on the combined measurement of the carbon monoxide and the oxygen content of the flue gas offers a promising alternative to currently applied oxygen based burnout control systems.

Further investigations should focus on biomass furnaces with differently shaped CO-O_2-characteristics, for which the approximation with a parabola is probably not sufficient. Examples could be medium- and large-scale furnaces, for which the CO-O_2-characteristic has typically sharper increases on the left side and is flatter on the right side of the characteristic. Other scientifically interesting applications are batch processes, as for example log wood furnaces, where the optimal excess air ratio is changing over time.

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Nomenclature

c_{O_2}	vol% w.b.	oxygen concentration (KS1D)
c_{CO}	$mg\,m^{-3}$ 13 vol% O_2 w.b.	CO equivalent KS1D sensor signal
$c_{CO,FGA}$	$mg\,m^{-3}$ 13 vol% O_2 d.b.	carbon monoxide concentration (flue gas analyzer)
$c_{O_2,FGA}$	vol% d.b.	oxygen concentration (flue gas analyzer)
T_f	°C	feed temperature
T_R	°C	return temperature
$\dot{Q}$	kW	thermal load
w_{H_2O}	wt% w.b.	fuel moisture content on wet basis
x	–	parameter of the CO-O_2-model
λ	–	air-fuel ratio

Acronyms and Indices

MBC	model based control
PID	proportional-integral-derivative (controller)
NL	nominal load
PL	partial load
opt	estimated optimal value
FGA	measured by flue gas analyzer

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