Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
August 29–31, 2007, Palma de Mallorca, Spain
ISBN Hardcopy: 978-0-88986-689-8 / CD: 978-0-88986-690-4

IMPROVED CONTROL OF A SMALL-SCALE BIOMASS BOILER

Bohumil Sulc, David Klimanek,
Department of Instrumentation and Control Engineering
Jan Hrdlicka
Department of Fluid Dynamics and Power Engineering
Czech Technical University in Prague
166 07 Prague, Technicka 4
Czech Republic
Bohumil.Sulc@fs.cvut.cz, David.Klimanek@fs.cvut.cz, Jan.Hrdlicka@fs.cvut.cz

ABSTRACT

Current European Union environmental policy aims at greater utilization of renewable energy sources. However, when operating bioenergetic devices we can face problems caused by a hidden increase in harmful emissions. This increase is caused by a gradual loss of the proper function of the control variable sensor. As will be shown, if the control variable sensor produces biased data, there is a danger that undesirable harmful emissions, above all emissions of CO and NO_X, will increase and will remain unrecognized. This paper will show how control enhanced by adding model-based discredibility detection can improve the ecological operation of a device. An experimental Verner biomass boiler equipped with an oxygen sensor is used as a specific example of a technical solution.

KEY WORDS

Small biomass boiler, oxygen sensor discredibility detection, incipient faults

1. Biomass as an energy source

The current policy of the European Union supports increased utilization of renewable energy sources. In European conditions, biomass is one of the most promising renewable energy sources. In Czech legislation, biomass has been introduced as a favored material for various ways of utilizing its energy content. Biomass is specified as a material that can originate from agriculture, forestry, the food processing industry, the wood and paper industry or as wooden waste from the civil engineering industry. There is one restriction – the material (especially wooden waste) must not contain halogenated organic compounds and heavy metals [2]. Such compounds are often used as wood preserving agents or paints. Several kinds of biomass materials are available in the Czech Republic for power production. They can be divided into two groups; the overview also includes materials that do not comply with the definition above:

a) specially grown biomass for power production
  - sugar beet, grain, potatoes – for ethanol production,
  - oil plants (e.g. rape or sunflower) – for producing raw oils and their methyl-esters,
  - energetic plants (e.g. salix, poplar, sorrel, alder, phalaris, hemp and other tree-like and grass-like species) – mainly used for direct combustion, but also usable for pyrolysis and gasification. This last group is becoming very important and promising, but currently it is not widely used,
  - Table 1 and Table 2 contain examples of plants for use as fuels together with their harvesting properties and some economics considerations.

b) waste biomass
  - vegetable residues from agriculture – e.g. straw (originating from grain, rape, corn, etc.) or wooden wastes from parks,
  - residues from animal husbandry – e.g. excrement or residues of feedstuffs,
  - organic solid household wastes and sludges from water treatment plants,
  - organic wastes from food processing plants – e.g. wastes from sugar mills, distilleries, residues from sawmills (sawdust, chips),
  - wastes from forestry – from wood harvesting and treatment, e.g. logs, chips, branches or bark [3],[4].

1.1 Replacement of solid fossil fuels

Biomass can provide the some range of fuel types as fossil fuels. Through various processes (e.g. drying, gasification, digestion, etc.) it can provide solid, liquid, and gaseous fuels.

Biomass can combust either homogeneously (volatile combustibles) or heterogeneously (non-volatile combustibles), like any solid fuel. The process itself has several phases:

- the fuel is died at temperatures up to 105 – 110 °C. In this phase, the moisture is evaporated and the volatile matter begins to be released.
- volatiles are released in the range approximately from 170 – 400 °C. Some portions of the volatiles decompose. The product is flammable

gaseous blend that contains H_2, CO, CO_2 and a mixture of hydrocarbons C_xH_y.

- the volatile combustibles are combusted. When the ignition temperature is reached (or an outer ignition source is used at lower temperatures), the released volatiles ignite. The surface and width of the flame front expands. The burning volatiles speed up ignition of the non-volatile matter – for example, coal ignites at around 300 °C, whereas pure carbon (without volatiles) ignites at around 700 °C.
- combustion of non-volatile combustibles is the longest period of solid fuel combustion. It takes around 90 % of the total time, and most of the heat is released in this period. All the reactions are heterogeneous, and they are limited by access of oxygen to the surface.

The main difference between biomass and solid fossil fuels (e.g. coal) is that biomass contains more volatiles (70 – 85 %) than fossil fuels (50 – 60 %). This means that biomass burns with a longer flame and generally more quickly. The most time consuming combustion of the char is shorter.

1.2 Combustion devices for biomass

Three main categories of boilers for biomass combustion are used I Europe. There can be divided according to their thermal power output and design:

- *high power boilers* – with thermal power over 1 MW. Such boilers are usually installed in industrial areas, e.g. wood processing plants, using the plant's own products, often wastes.
- *medium-size power boilers* – with thermal output 100 kW – 1 MW. The main use of such devices is in local district heating plants or for heating small industrial buildings. Wooden chips or pressed straw are often used as fuel.
- *small power devices* – with power output up to 100 kW. These devices are mainly used in households or small company houses. This group includes stoves, open and closed fireplaces using wooden logs, and also automatic heating boilers that burn chips and pellets made of various materials – mainly wood but also pellets produced from grain residues or special plants for use as fuels [2], [3].

Table 3 contains an overview of different kinds of small combustion devices; automated boilers are shown in all categories.

2. Emission minimization in biomass combustion devices

When operating high power combustion devices there are limits on dangerous emissions of CO and NO_x. In addition, also carbon dioxide CO_2 emissions are strictly limited. CO_2 is one of the final combustion products of fuels containing carbon (including all kinds of biomass).

Table 1 Examples of costs for cultivating some types of plants for use as biomass in the Czech Republic [2]

Specie	**Annual direct costs [€/ha] ***	**Annual indirect costs [€/ha]**	**Total annual costs [€/ha]**	**Yield of dry mass – autumn [t/ha]**	**Total annual costs – autumn [€/t]**	**Yield of dry mass – spring [t/ha]**	**Total annual costs – spring [€/ha]**
Hemp	444	111	555	10	55	7	79
Millet	360	118	478	15	32	9	53
Phalaris	168	113	281	8	35	5,8	48
Fescue	168	113	281	7,5	37	5,3	53
Miscanthus	698	135	832	15	55	11,7	71
Sorrel	444	111	555	10	55	—	—

* average costs including farming, fertilizing, harvesting and transportation

Table 2 Some kinds of plants for use as biomass, and their important properties [2]

Specie	**Autumn harvest**		**Spring harvest**			
	W [%]	Yield of dry mass [t/ha]	W [%]	Yield of dry mass [t/ha]	Moisture decrement [%]	Yield decrement [%]
Phalaris	50	7,21	19	5,22	31	27,3
Hemp	52	10,25	26	7,06	26	31,1
Millet	66	3,22	12	5,76	24	37,5
Fescue	48	7,25	19	5,15	29	28,9

Table 3 Types of combustion devices with automated fuel feeding [2]

Type	Power output range	Fuel	Acceptable fuel humidity [%]
Boilers with bottom fuel feeding	10 kW – 2,5 MW	Wood chips and pellets, ash max. 1 %	5 – 50
Moving grate boilers with front fuel feeding	100 kW – 15 MW	All kinds of biofuels, ash max. 50 %	5 – 60
Rotating grate boilers with bottom feeding	2 – 5 MW	Wood chips with high water content, ash max. 5 %	45 – 60
Gasification boilers	20 kW – 1,5 MW	Dry wood chips, ash max. 5 %	5 – 35
Boilers for pellets with top or front feeding	2,5 – 30 kW	All kinds of pellets	up to 15
Boilers with a drum combustion chamber	2 – 10 MW	Sawdust, wood shavings and other residues up to 5 mm	up to 20
Boilers with a bubbling fluidized bed (BFB)	5 – 15 MW	Any kind of biofuel up to 10 mm size	5 – 60
Boilers with a circulating fluidized bed (CFB)	15 – 100 MW	Any kind of biofuel up to 10 mm size	5 – 60
Pulverized coal boilers	100 – 1000 MW, co-firing with coal up to 10 % wt. biomass	Wood 2 – 4 mm, straw up to 6 mm, miscanthus up to 4 mm particle size	up to 20

In the quest to produce the lowest achievable gaseous emissions and to maintain steady fuel combustion, it is necessary to control the air factor (air excess) λ, at a desired value. The air factor λ is expressed by the ratio

$$\lambda = \frac{Q_a}{Q_{a\,min}} > 1 \quad [-] \tag{1}$$

where Q_a is the flow rate of the actual combustion air and Q_{amin} is the necessary (stoichiometric) burning air. The topical value of the air factor λ in the running combustion process is acquired via oxygen concentration measurement in the flue gases at the end part of the boiler. Fig. 1 depicts the optimal range of the air factor. If the air factor is between α_{min} and α_{max}, the emissions of CO and NO_x will not exceed the maximum acceptable level. However, the problem is that oxygen probes are vulnerable to faults [12]. If the oxygen probe starts to provide biased information about the oxygen content in the flue gases, the emissions of CO and NO_x may be excessive, and penalties can be incurred for undesirable environmental impacts. Thus it is essential to avoid any unrecognized increase in emissions, particularly of CO and NO_x, through oxygen sensor discredibility detection.

Oxygen sensor discredibility does not mean that that the sensor is out of function, but that its properties have gradually changed to the extent that the sensor has started to provide biased data.

3. Experimental power boiler for oxygen sensor discredibility detection testing

The problem of control variable sensor discredibility detection can demonstrated on the Verner A25 pilot experimental power boiler (Fig. 3), which is available in the CTU labs. The Verner A25 is an automated boiler for heating water production with electric ignition. All kinds of biomass pellets can be used as fuel. According to the manufacturer, the nominal power output for wood is 25 kW and for grain pellets 18 kW. A specific feature of the boiler is that the combustion chamber has a trapezoidal cross-section and it is equipped with a moving steel grate. The primary combustion air passes through the grate from below and the secondary air is injected through holes in both sides above the grate. The air is fed into the boiler by an air fan that is controlled (together with the fuel feeder) by the controller unit. The unit controls the operation of the boiler, e.g. rate of feeding, amount of air or movement of the grate, and allows manual changes in the operation settings. Fuel is fed from the storage bin into the combustion chamber by a screw feeder. The feeder is connected to the rear wall of the combustion chamber above the grate in such a way that the fuel falls onto the grate. The fuel starts to burn on the rear side of the chamber and is moved by the grate to the front side, still burning. The ashbin is placed below the grate. The fine

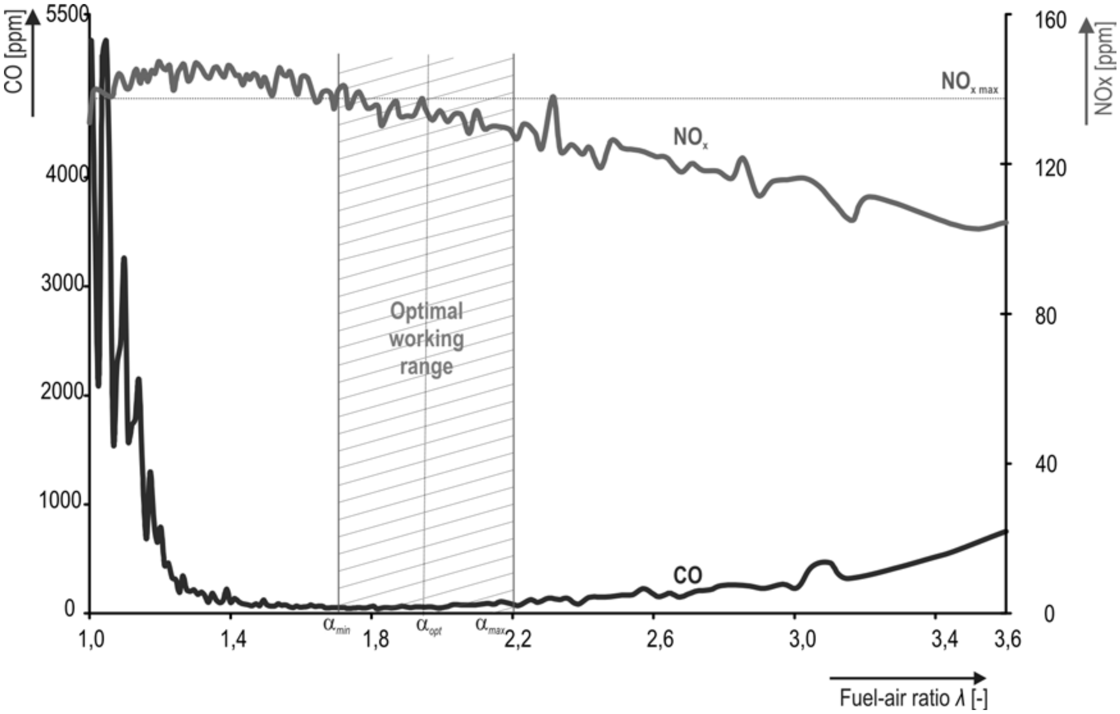

Fig. 1Optimal operating range in dependence on the fuel - air ratio [2]

ash particles fall into the ashbin through the grate, and the rest of the ash (and any unburned material) is moved into the bin by the grate on its front edge. The flue gases leaving the chamber pass through the heat exchangers to the chimney. The boiler is connected to the partially closed water cycle, which is driven by a water pump. Two connections are made in the water cycle – the pipe delivering cold water is connected at the lowest point of the cycle before the entrance into the boiler, and at the top of the cycle there is a connection that removes excess hot water. There are also points for temperature measurements and a sampling point for flue gas analysis in the exhaust tube.

THE experimental set-up includes the following parts. In the flue gas exhaust, an oxygen probe has been experimentally placed in order to measure the oxygen content in the flue gases. About one third of the flow of flue gases is brought back into the combustion chamber by a tube. The flow rate of the air supplied by the fan into the combustion chamber is manipulated by a valve and controller with the aim to keep a certain share of the oxygen in the flue gases at a desired value. This provides a guarantee of optimal combustion, with minimal emissions.

However, we may face the problem of gradual changes in the oxygen sensor. Generally, if the property changes of a control variable 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 tro be working property. The influence of changes in the oxygen sensor properties on the control process is depicted in Fig. 2. It is apparent that when the oxygen sensor starts to provide biased data, the oxygen control loop reacts to incorrect information about the fuel/air ratio by attempting to remove the unreal control error.

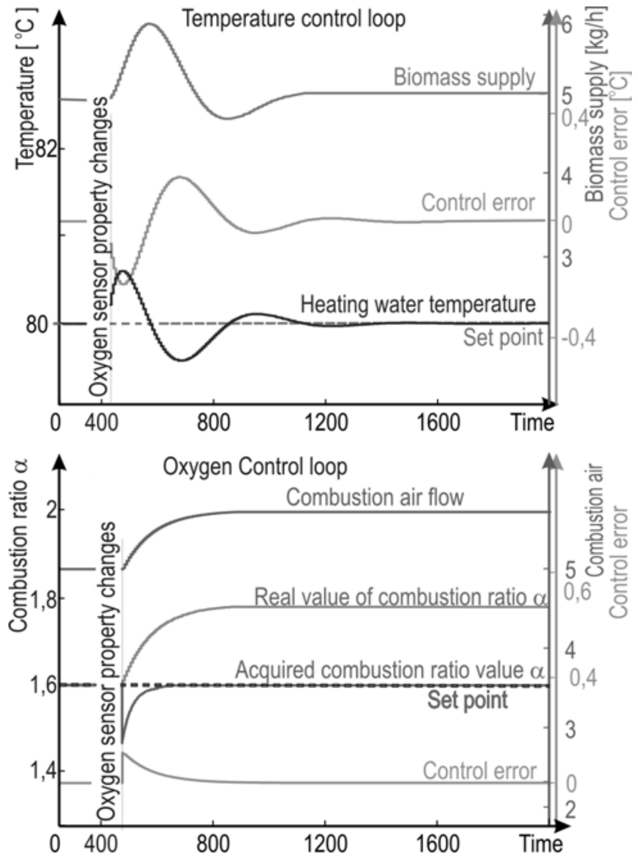

Fig. 2Impacts of changes in the oxygen sensor on the control loop signals

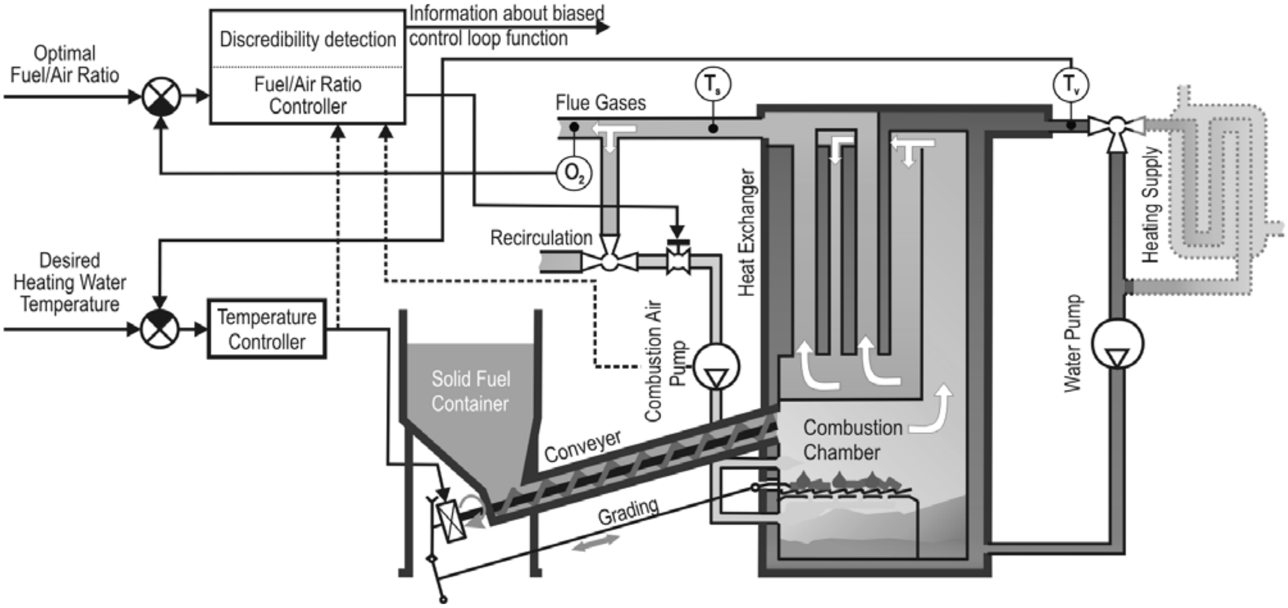

Fig. 3Scheme of the experimental pilot power boiler with oxygen sensor discredibility detection

The main loop of the heating water temperature control works properly, because it returns the control error back to zero. The desired temperature value can be achieved at the cost of increasing the fuel supply, because the oxygen control loop has changed the combustion air delivery, so environmental impacts will occur but they will remain unrecognized.

To avoid undesirable side effects resulting from control variable sensor discredibility, sensor discredibility detection either by hardware or by software can be used. Hardware discredibility detection is usually achieved by adding another redundant sensor. This may be a costly solution. The cheapest solution is offered via software, and we are currently investigating ways of doing this. Generally, the aim of our research is to extend the function of a standard controller, so that it will be able, to discover impreciseness in the control loop operation, while continuing to fulfill its normal control function.

4. Overview of model-based sensor discredibility detection

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 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 is informed, and he or she may either replace the control variable sensor or perform other safety measures. A graphical user interface has been developed. It offers a selection of methods for residuum minimization. The residuum can be minimized using:

- the standard genetic algorithm,
- the simulated annealing algorithm,
- the least square method.

Before any implementation in a control loop, it was necessary to test the proper function of the designed procedures by simulation. Therefore, the methods were applied to simulated examples of a control loop. The controlled objects were a cascade of two tanks (the control variable was the level in the second tank [13]), and a simplified model of the power boiler (Fig. 3) [12]. Matlab–Simulink is used for modelling.

Simulated experiments on the proposed model-based discredibility detection method have proved its ability to indicate control variable sensor changes, together with discredibility detection. This method informs the operator about the estimated time until the occurrence of sensor discredibility. If the time is critical, the operator also receives a warning about the situation. No difference was found between the algorithms used here. Their good convergence depends mainly on the algorithm settings.

5. Conclusion

This paper discusses the use of renewable energy sources in the Czech Republic. Undesirable emissions when operating renewable energy sources are linked mainly with the technical construction of the boiled. The often neglected biased control variable sensor function in bioenergetic processes (especially in biomass boilers) has an important impact on the production of harmful emissions. In this paper we have shown how equipment in the field of control can improve the ecological operation of a device. As a specific example of a technical solution, an experimental Verner biomass boiler equipped with an oxygen sensor was used. Any malfunction of the oxygen sensor is detected by the software. The detection of discredibility was tested with a Matlab/Simulink model designed using engineering modeling. The positive results will be used in higher power combustion devices, in which oxygen sensor malfunction detection will be of great ecological and economic importance.

Acknowledgements

This research has been supported by project MSM 6840770035.

References

[1] M. Kaltschmitt, H. Hartmann, *Energie aus Biomasse* (Berlin, Springer-Verlag, 2001). ISBN 35–4064–853–4.

[2] T. B., Reed *Biomass Gasification: Principles and Technology* (Noyes Data corp., 1981). ISBN 08–1550–852–2.

[3] J. Hrdlička, F. Hrdlička, Combustion of Grain Pellets – Research Results, *European Pellets Forum 2006* [CD-ROM], Wels, Austria,.2006.

[4] J. Hrdlička, F. Hrdlička, R. Verner, Possible Use of Energetic Plants in Small Scale Combustion, *Nordic Bioenergy Conference 2005* [CD-ROM], Trondheim, Norway, 2005.

[5] D. Klimánek, *Detection of a Biased Control Loop Function via Evolutionary Algorithms* PhD. Thesis. (CTU in Prague, 2007).

[6] R. King, *Computational Intelligence in Control Engineering* (Basel, Prentice-Hall, 1999). ISBN 08–2471–993–X.

[7] J. Chen, R. Patton, *Robust Model Based Fault Diagnosis for Dynamic Systems*, (New York, Kluwer Academic Publisher, 1999). ISBN 07–9238–411–3.

[8] J. Korbic, *Fault Diagnosis: Models, Artificial Intelligence, Applications* (Berlin, Springer, 2004). ISBN 35–4040–767–7.

[9] P. Neuman, B. Sulc, P. Zitek, T. Dlouhy, Non-linear Engineering Simulator of a Coal Fired Steam Boiler Applied to Fault Detection of Optimum Combustion Control, *Preprints of the 4th Symposium on Safety Processes (IFAC)*, 2002, 927–932.

[10] J. Hlava , B. Sulc, J. Tamáš, A Laboratory Scale Plant with Hybrid Dynamics and Remote Access via Internet for Control Engineering Education, *Preprints of the 16th World Congress of the International Federation of Automatic Control* [CD-ROM]. 2005.

[11] R. Koushanfar, On-line Fault Detection of Sensor Measurements, *Proceedings of IEEE Sensors 2003, 2*(8), 2003, 974–979.

[12] D. Klimanek, B. Sulc, Improvement of Control Loop Function by Control Variable Sensor Discredibility Detection, *Transactions of the VSB–Technical University of Ostrava*, 2006, 120–126. ISBN 80–248–1142–1.

[13] D. Klimanek, B. Sulc, Sensor Discredibility Detection by Means of Software Redundancy, Proceedings of the 7th International Carpathian Control Conference, 2006, 249–252. ISBN 80–248–1066–2.

[14] M. Mehranbodn, C. Panjapornpon, A Method of Sensor Fault Detection and Identification, *Journal of Process Control*, *15*(3), 2005, 321-339. ISSN 0959–1524.