SMALL AND MEDIUM SCALE BIOMASS COMBUSTION CONTROL POSSIBILITIES

Viktor Plaček, Cyril Oswald
Czech Technical University in Prague, Faculty of Mechanical Engineering
Technická 4, Praha 6, Czech Republic
viktor.placek@fs.cvut.cz, cyril.oswald@fs.cvut.cz

ABSTRACT
Biomass combustion is one of the most versatile and spread heat source for residential usage in the world. Nowadays a lot of new combustion devices in developed countries are controlled automatically. The control algorithm used in these devices is crucial in attaining optimal service economy with minimal environmental impact. This contribution deals with two ways how to implement proper control algorithms to small and medium scale boilers. The first method is by applying modern methods of controller development and the second by adapting tested algorithms from full-scale boilers. The used algorithms are implemented and tested on experimental devices based on common market products.

KEY WORDS
Biomass, combustion, control, environmental

1. Introduction

Biomass combustion for residential heating has a long tradition worldwide. Biomass fuel is still commonly available in a form of wood or herbal fuels or in a form of organic waste dedicated for recycling. The biomass has its substantial share in environmentally friendly energy sources due to its carbon dioxide neutrality (CO₂ emitted during biomass combustion was previously took away from atmosphere during biomass grow cycle). [1][2]

The efficiency and environmental influence of traditional manually operated devices were reliant on the skill of a user. The effort to achieve a higher economy of the combustion process and to eliminate the need of an operator care led to introduction of automatic combustion devices. Automatic biomass combustion devices are commonly service undemanding similar to as for example automatic gas combustion devices. [1]

A construction of automatic combustion devices followed a long and thorough development of the manually controlled ones. The construction of modern biomass boilers produced in developed countries are already on bounds of its possibilities. One of the ways of improving efficiency and reducing harmful emissions is to develop effective control algorithms. [5][6][8]

The algorithms used in automatic small-scale boilers are usually based on experience with their manual operation. Most of the algorithms were created heuristically by trial-and-error method during production of the devices. These algorithms do not have ground in modern control algorithm design methods. The heat output control of a lot of commonly used small-scale boilers is even nowadays based on simple on/off algorithm – when the temperature of heating water drop the boiler fire up and works on its nominal heat output until heated water temperature raises to its set-point again. [5]

Only part of modern small-scale boilers utilizes at least some sort of fuel feeding modulation. Careless control algorithms can cause process variables transitions that raise emission of harmful flue gases and lower the efficiency. Such interferences to combustion process can be so significant that some of the automatic boilers advantages – the economy and ecological operation - can be markedly spoiled. [5][9]

Full-scale boilers control algorithms, unlike small-scale ones, have undergone skilled and expensive development. A lot of full-scale control algorithms are bounded to rather expensive instrumentation and control equipment. The price of the instrumentation is one of the factors that keeps the full-scale algorithms being applied to small and mid-scale boilers. [2][8]

Small-scale boilers have also other factors that make usability of full-scale algorithms problematic. These are for example:

- operation by unskilled persons,
- neglected maintenance,
- low-price unreliable sensors,
- fuel of unknown and changing quality,
- low budget for instrumentation and control, etc.

Combustion process in small-scale boilers has also significantly faster dynamics due to smaller masses of combusted fuel and lining. Also the sensitivity to disturbances is more significant in comparison with full-scale boilers. [7]

Authors’ work is based on an assistance to small and mid-scale boiler manufacturers in the field of control algorithms development. The aim is to improve boiler properties without the need of changing construction of a device or equipping the device with additional instrumentation – both potentially leading to an increase of manufacturing costs.

There were successfully applied linear controllers on simple small-scale boilers as a replacement of simple
on/off heat output control. The linear controllers showed themselves as able to properly control heat demand changes and eliminate noticeable transitions during lower than nominal heat demand.

An optimizing algorithm was successfully implemented and tested on medium-scale boiler. The algorithm is able to properly control combustion process to work in optimal combustion conditions even without the need of an oxygen sensor.

2. Experimental Background

Two experimental combustion devices were built in order to verify theoretical knowledge based on a computer simulation. The small-scale hot water boiler with 25 kW nominal heat output and mid-scale boiler with 100 kW nominal heat output.

Figure 1. Schematic view of the small-scale boiler

Both experimental devices use custom made control unit RexWinLab-8000 that was developed at the department of the authors. The RexWinLab-8000 control unit is based on PAC (Programmable Automation Controller) WinPAC produced by company ICP DAS. However, the original firmware of the controller has been replaced by REX Control – specialized development and control software developed at the University of West Bohemia in Pilsen. REX Control allows us to develop algorithms in graphical environment similar to Matlab/Simulink tools. Apart from common algorithmic blocks, that usually control algorithm development tools have, the software also contains advanced control algorithms such as fuzzy controllers or neural networks. Finished algorithm can then be compiled and downloaded to the controller and executed in real-time. The software also allows real-time communication with Simulink using Ethernet interface. This feature is used for real-time experiment monitoring, logging and control.

2.1 Small-scale Boiler

The small scale experimental combustion device is based on a common market accessible hot water boiler named Verner A25G dedicated to residential heating. Its nominal heat output is 25 kW when combusting wood pellets.

Figure 2. Communication of the controllers

![Figure 2. Communication of the controllers](image)

Figure 3. The experiment with heat output control. Fuel feeding modulation algorithm from the manufacturer (on the left) and PID controller algorithm (on the right).

![Figure 3. The experiment with heat output control](image)
The boiler is provided with its own control electronics allowing only a couple of basic manual adjustments. Original electronics was unusable for our experimental works, so we replaced original control electronics with custom made switchbox equipped with the above mentioned control unit RexWinLab-8000.

For experimental purposes the boiler was equipped with additional instrumentation. The blow fan drive with fixed air flow delivery was equipped with frequency changer for continuous combustion air supply control. Three thermocouples were added for more complex temperature field measurement. A flue gas analysis unit was installed in the stack entrance (Figure 1). The switchbox was designed in a way that it is anytime possible to switch back to original control electronics when demanded. The additional instrumentation is installed just for better understanding of the process during experiments and it is not intended to be installed in a market boiler version.

2.2 Mid-scale Boiler

The medium-scale boiler is custom-made experimental device produced by the company Fiedler for the purpose of control algorithms development. The boiler has nominal heat output of 100 kW when combusting wood chips. It has a specially made grate and a thermally isolated combustion chamber so that it could combust fuel of low quality (unlike the small-scale boiler that has combustion chamber with water jacket).

The boiler was supplied with a standard control unit based on Siemens PLC (Programmable Logic Controller) pre-programmed with a company standard control algorithm. The boiler switchbox was then additionally fitted with RexWinLab-8000 control unit for the formerly mentioned advantages. This configuration was chosen so, that it would enable us to compare the combustion process quality of the standard manufacturer’s algorithm control and the newly developed algorithms.

All standard sensors and control members are connected to hardware inputs and outputs of Siemens controller. Additionally installed sensors (e.g. water flow sensor, flue gas analysis unit) and control members are connected to RexWinLab-8000 unit (see Figure 2).

When the process is controlled by standard manufacturer algorithm, all the control service is done by the Siemens controller. RexWinLab-8000 just monitors values of the measured and the manipulated variables and writes it to a log file for offline analysis. When testing newly developed algorithms, the control job is done by RexWinLab-8000 control unit. It acquires measured variables values from Siemens via MODBus and additional measured variables values via its own hardware inputs. Standard manipulated variable values are sent to the subordinate Siemens controller output via MODBus and additional manipulated variable values are controlled via RexWinLab-8000 own hardware outputs.

3. Algorithms Development

The main control issues to be solved were identified in co-operation with the manufacturers and by experimental measurements. One of the issues was a method of a heat output control used on the small-scale boiler.

Originally, the heat output of the small-scale boiler was controlled by using a modulation of fuel feeding. When the temperature of the heated water raised above a set point temperature, the controller switched off the fuel feeding. After the temperature of hot water started to drop, the controller raised the fuel feeding in steps again (see Figure 3 on the left). The heat output control algorithm of the manufacturer was created heuristically with experience based on the previous experiments. During the controller action the combustion process fluctuated considerably and emitted high amounts of unburned flue gas. The economy and ecology of the boiler was significantly lowered during the transitions.

It was decided to replace the original control algorithm with a continuous PI (proportionally integrative) control algorithm in order to eliminate combustion process fluctuation and, at the same time, harmful flue gases emission.

First, a couple of experiments were carried out to find out proper work point of controlled and manipulated variables at 25 kW heat output. A simple analytical thermo-mechanical model was then created. Based on previous experiments the mathematical model in the form of linear differential equations was estimated. The mathematical model was then used as an input to Compensation of Dynamics method used to estimate proper parameters of PI controller algorithm. A couple of experiments were carried out to tune the estimated parameters. As a result the combustion process fluctuation was eliminated (see Figure 3 on the right) for nominal heat output. The same PI controller parameters allowed to control heat output down as low as 40 % of nominal value.
4. Full-scale to Mid-scale Algorithms Transfer

A transfer of algorithms from full-scale boilers to boilers with lower heat output is problematic for the reasons mentioned in the Introduction. Even though, when all the issues of the transfer are resolved, the algorithm transfer can be easier than development of a complete new one.

Figure 4 shows a general principle that manifests itself on almost any boiler regardless its heat output level. When the combustion air flow is lowered the air to fuel ratio of combustion process is changed too. The excess of air in comparison with theoretical stoichiometric requirement is thus decreased too. If the excess of air is low a lot of carbon monoxide is generated. The carbon monoxide is not only harmful flue gas but it can also be further oxidized to carbon dioxide accompanied by a heat release. Emission of carbon monoxide is thus not only non-ecological but also uneconomical. The lowered economy is caused by a drop of the efficiency. [1][2][3]

Oppositely, when the excess of air is too high the combustion process is chilled and the carbon monoxide emissions rise, too. Moreover, the raised airflow causes higher stack loss and spoils the efficiency again. For that reason, the excess air ratio must be carefully controlled in an optimal range. Unfortunately, the excess air optimal range is dependent on a current heat output and fuel quality.

The control of the excess air ratio in the optimal range is on full-scale boilers commonly accomplished by using an oxygen sensor for measuring oxygen residual in the flue gas. The most common and cheapest oxygen sensor is a broadband lambda probe. The control circuit of the method is depicted in Figure 6. The controller uses oxygen concentration feedback to manipulate airflow rate and keep combustion air excess in optimal range. [3][4]

Usage of lambda probe in small-scale and partially also in medium scale boilers has its drawbacks. Its price is still not marginal (mainly for small-scale boilers) and its reliability for a long time unattended usage is doubtful. It is also very sensitive to contamination of some substances. Development of an algorithm that would be able to control the excess air ratio without a need of a lambda probe would be probably the best solution of the matter.[3]

Figure 5 depicts the time record of experiment with an optimization algorithm that should be able to accomplish the task of excess air ratio control without using a lambda probe. The algorithm co-operates with the above mentioned PI controller used for heat output control. The optimization algorithm monitors the fuel consumption by measuring fuel feeding conveyor duty and controls the combustion air flow by changing the frequency of the combustion air blower fan electromotor. The control circuit of the optimization algorithm is depicted in Figure 7.

The algorithm changes the excess air ratio and waits until heat output controller attain a steady state. Then the algorithm evaluates the fuel consumption needed for the current heat output. Then the algorithm raises or decreases excess air ratio and again waits for steady state and evaluate the fuel consumption. This process is repeated until the change of excess air ratio would only increase

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Figure 6. Algebraic scheme of a common method of combustion airflow rate control using a lambda probe.

Figure 7. Algebraic scheme of an optimization algorithm able to control airflow without a need of a lambda probe.

Figure 5. The experiment with the excess air ratio optimization algorithm control.
the fuel consumption for current heat output.

The algorithm success in attaining the highest economy and the lowest environmental impact is based on the fact that the lowest fuel consumption means the highest efficiency and simultaneously the lowest CO emissions. The excess air ratio is in optimal range (see Figure 4).

5. Conclusion

The development of new control algorithms for small-scale boilers still has possibilities for improvement. Transfer of tried and tested algorithms from full-scale boilers to small-scale boilers has its issues. For that reason the development of new algorithms from scratch with the help of modern control algorithms methodology is often easier than adapting full-scale proved algorithms.

Usage and tuning of linear controller algorithm instead of two-state on/off control was shown and successfully tested on a device with a construction of a common-market boiler. The newly used algorithm is able to eliminate transients disturbing the combustion process and thus significantly improve its economy and environmental cleanness.

For a mid-scale boiler, the way of transfer, a principle proven from full-scale boilers, was implemented. Optimization algorithm was proposed based on the principle of the optimal combustion conditions when the combustion efficiency is the highest.

The optimization algorithm proved to be able to find the optimal excess air ratio without the need of additional instrumentation in a form of lambda probe. The usage of optimization algorithm saves investment costs of a new device but is also independent on a possibly unreliable sensor.

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