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Model based control of a small-scale biomass boiler

Markus Gölles [a,*], Stefan Reiter [a,b], Thomas Brunner [a,c,d], Nicolaos Dourdoumas [b], Ingwald Obernberger [a,c,d]

[a] BIOENERGY 2020+ GmbH, Inffeldgasse 21b, 8010 Graz, Austria
[b] Institute of Automation and Control, Graz University of Technology, Kopernikusgasse 24, 8010 Graz, Austria
[c] Institute for Process and Particle Engineering, Graz University of Technology, Inffeldgasse 13, 8010 Graz, Austria
[d] BIOS BIOENERGIESYSTEME GmbH, Inffeldgasse 21b, 8010 Graz, Austria

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ABSTRACT

Because of increased efforts to reduce CO_2 emissions a significant step in the development of small-scale (residential) biomass boilers for space heating has been achieved in recent years. Currently, the full potential for low-emission operation at high efficiencies, which is in principle possible due to optimized furnace geometries as well as combustion air staging strategies, cannot be exploited since there is still the need to enhance the controllers applied. For this reason, a model based control strategy for small-scale biomass boilers was developed and successfully implemented in a commercially available system. Thereby, appropriate mathematical models were developed for all relevant parts of the furnace and connected to an overall model subsequently used for the control unit design. The resulting controller is based on the input–output linearization and the state variables are estimated by an extended Kalman filter. Finally, the new control was implemented at a commercially available small-scale biomass boiler and the experimental verification showed a significant improvement of the operating behaviour in comparison to the conventional control.

1. Introduction

The substitution of fossil fuels by solid biomass in residential heating systems can make a contribution to reduce the CO_2-emissions. For this reason, great efforts have already been made to further develop small-scale (residential) biomass boilers for space heating and a significant technological step has been achieved in recent years. However, currently the full potential for low-emission operation at high efficiencies, which is in principle possible due to optimized furnace geometries as well as combustion air staging strategies, cannot be exploited since there is still the need to enhance the controllers applied. In terms of system theory a biomass boiler is a nonlinear, coupled multivariable system with several inputs (fuel feed, air supply, etc.) and several outputs (power output, residual oxygen content of the flue gas, etc.). But the couplings and nonlinearities are just partially or even not at all considered in the control strategies currently applied. They are basically based on decoupled control circuits with linear controllers (e.g. Good, 1992; Padinger, 2001). Furthermore, each manufacturer traces his own control strategy and there is no consistent, methodical approach available up to now.

Within the last years several groups worked on the application of model predictive control in medium- and large-scale biomass furnaces typically used in district heating plants or combined heat and power plants. They mainly use linear or linearized models and up to now most of the work is restricted to simulation studies and does not go further to a real industrial implementation (e.g. Leskens, van-Kessel, & Bosgra, 2005; Paces, Voigt, Jakubek, Schirrer, & Kozek, 2011; Kortela & Jms-Jounela, 2012).

Another approach for medium-scale biomass plants based on comparatively simple but nonlinear models has been developed at the research centre BIOENERGGY2020+ in cooperation with the Institute for Automation and Control, Graz University of Technology (Bauer, 2009; Gölles, Bauer, Brunner, Dourdoumas, & Obernberger, 2011). Thereby, the system is described by a nonlinear, fifth order state space model and the control unit design was performed on the basis of the input–output linearization with the state variables estimated by an extended Kalman filter. The final implementation and verification of the control at a medium-scale biomass furnace (horizontally moving grate, hot water boiler) firing wood chips with a nominal boiler capacity of 180 kW led to a significant improvement of the operation behaviour. Because of the lack of available actuators and the resulting stronger couplings in small-scale residential biomass boilers the potential for improvement by a comparable control strategy would be even higher.

For this reason the objective of the work described in this paper was to develop a control strategy similar to the already available

* Corresponding author. Tel.: +43 316 873 9208; fax: +43 316 873 9202.
E-mail address: markus.goelles@bioenergy2020.eu (M. Gölles).

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Nomenclature

d	disturbance variable (various)
m	mass (kg)
n	order (dimensionless)
$\dot{m}$	mass flow (kg/s)
$\dot{Q}$	heat flow (W)
r	set point (various)
T	temperature (K)
t	time (s)
t_d	dead time (s)
u	input variable (various)
v	output variable of PI controller (various)
v	measurement noise (various)
w	mass fraction (dimensionless)
w	plant (process) noise (various)
x	mole fraction (dimensionless)
x	state variable (various)
x	output (control) variable (various)

Greek symbols

Δp	pressure difference (Pa)
λ	air ratio (dimensionless)
ρ	relative degree (dimensionless)

Abbreviations

d.b.	dry basis
w.b.	wet basis

Subscripts

ad	adiabatic
ds	dry substance
eq	equilibrium (steady state)
f	fuel
fa	false air
fb	fuel bed
ff	fuel feed
fg	flue gas
fg,in	flue gas inlet of the heat exchanger
H_2O	water
he	heat exchanger
inlet	at the fuel inlet
O_2	oxygen
pa	primary air
ret	return
sa	secondary air
thd	thermal decomposition
w	water
wev	water evaporation

control for medium-scale furnaces on the basis of a representative small-scale wood chip combustion system.

In the first step appropriate models for all relevant parts of the boiler were developed and experimentally verified on the basis of a commercially available small-scale biomass combustion system (depicted in Section 2). The individual models are outlined in Section 3. The developed sub-models were connected to an overall model (Section 4.1) which was subsequently used as a basis for the control unit design (Section 4.2). The resulting controller requires all state variables but only one state variable can be measured. For this reason an extended Kalman filter was developed to estimate the state variables (Section 4.3). Finally, the control was implemented at the investigated small-scale boiler and experimentally verified. The main changes of the operating behaviour are illustrated in detail in Section 5.

2. Biomass boiler investigated

The boiler investigated is a commercially available unit commonly used for residential heating (see Fig. 1). The plant is designed for the combustion of wood chips and has a nominal boiler capacity of 30 kW. The fuel is fed by a screw feeder (1) onto a tiltable grate (2), where the fuel is heated up because of the high temperatures. Subsequently, the water bound in the fuel is evaporated and the volatile components are released to the gas phase. Finally, the remaining charcoal is burned with the supplied air. Furthermore, the plant is equipped with a staged air supply, where just a part of the air is provided below the grate (primary air) and the rest is injected with high velocity (secondary air) further downstream in order to enhance a good mixing of the combustible gas with the oxygen of the air which decreases the pollutant emissions as well as the necessary excess air ratio and therefore increases the efficiency. With regard to the staged air supply the combustion zone is divided into a primary combustion zone (3a) which is surrounded by refractory lining and a secondary combustion zone (3b) which is already water cooled. The manipulation of the supplied primary and secondary air is performed by both a common rotatable air shutter (4) and the flue gas fan (6) which above all always must ensure an underpressure in the whole combustion zone to avoid an escape of unburnt gases through leaky areas. In the end, most of the heat released by the combustion is transferred to a water stream in the heat exchanger

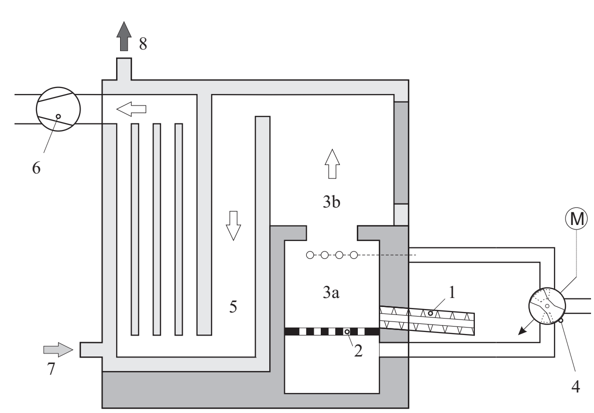

Fig. 1. Scheme of the small-scale biomass boiler investigated: (1) fuel feed, (2) grate, (3a) primary combustion zone, (3b) secondary combustion zone, (4) rotatable air shutter, (5) heat exchanger (boiler), (6) flue gas fan, (7) return, (8) feed.