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Mathematical Model of Biomass Boiler for Control Purposes

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This paper focuses on building dynamic mathematical model of biomass boiler of medium energy output (in units of MW) as a controlled system and the use of this model in practice. Model of controlled system will serve especially for research of new ways of industrial biomass boilers control and will provide a device for the optimisation of existing control systems. At first, area of automatic control of biomass boilers with medium energy output is described. Control of these boilers is with regard to their lowered dynamical properties considered problematic. Construction of the model is based on the heat and mass balance calculations made according to experimental data. These balance calculations serve to precise static properties of experimental unit for biomass combustion. Central part of the paper presents development of the final model that resulted from balance calculations and from analysis of step responses of the system obtained by measuring. Built dynamic model is compared with experimental data through simulations in Matlab/Simulink and verified.
For validation of its applicability, the model of controlled system is completed with control system and closed-loop control circuit is validated by simulation. Then the design of new controller configuration, which improves the quality of control considerably, is presented. At the final part of the paper, possibilities of other use of the model are given, both in control theory and in industrial practice.

1. Introduction

Compared to combustion of natural gas, biomass requires high quality combustion air flow control due to its varying properties. In addition to boiler technology (e.g. Grolig et al., 2010, presents application of cogeneration systems), control system configuration has also a significant impact on economical biomass utilization. Quality of control system is, however, dependent on finances. This paper focuses on biomass boilers of medium energy output (in units of MW) whose budget enables development and implementation of more sophisticated control systems as opposed to small scale heat sources.
Research aimed at constructing a dynamic mathematical model as a controlled system that is suitable for design or optimization of control system. Control systems of existing biomass boilers usually combine typical PID feedback control which is executed by

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programmable logic controller and personal computer (PC) functioning as operator control panel. If the controlled system allows, employment of PID controllers is very effective (e.g. in gas boilers). However, biomass combustion is a complicated process demanding a high quality control system. Recently, novel methods of control usually designated as advanced process control have been developed. Several of these novel approaches seem very promising in industrial practice and raise attention among researchers (Camacho and Bordons, 2004, deal with Model predictive control, MPC). Testing and potential implementation of novel control methods requires certain knowledge of mathematical model of controlled system (Mikleš and Fikar, 2007). These methods prove to be very efficient for optimization of common PID control (the so called PID tuning) where there is no possibility for tests in operations. Research of current publications showed that models are created mostly for individual components of heat production technologies (such as combustion chamber or heat exchanger) or for fossil fuel boilers (Haryanto and Hong, 2010; Keshavarz et al., 2010; Solberg et al., 2007; Mahlia et al., 2003). Dynamic mathematical model of biomass boiler applicable for control purposes has not yet been developed.

2. Boiler Description

Construction of the model used experimental data obtained by measuring at biomass boiler with inclined moving grate of 1 MW energy output designated for hot water heating. Fig. 1 presents a simplified flow sheet of the experimental unit. Boilers are made up by several technologies which only recently have started to be used in medium energy output units on a large scale. This involves flue gas recirculation (recycle), combustion air preheating (heat exchanger HE2) and separation of combustion air flows into primary and secondary ones and their supply into designated areas of combustion chamber.

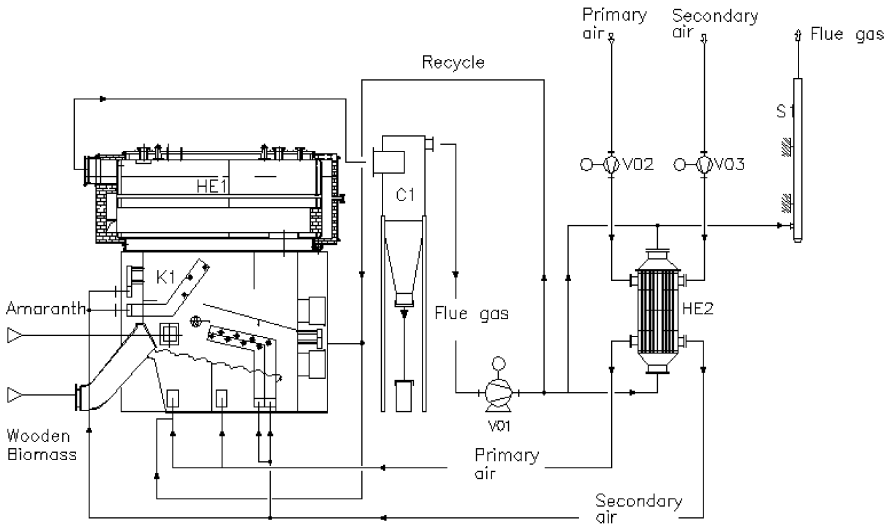

Figure 1: Simplified flowsheet of the experimental unit

3. Methodology

First step of model construction involved selection of input and output variables for measuring and assessment. This was performed using common approaches to control of these systems (Table 1). The so called balance model of the boiler was created; this model based on energy and mass balances provides important information about prospective operating conditions, such as consumption of combustion air/fuel and amount and composition of flue gas. The model describes static behaviour of the system. Creation of this model is linked to W2E software (Touš et al., 2009). Description of dynamic behaviour of the system employs repeated analyses of step responses of the system obtained by measuring.

Table 1: Overview of quantities for system identification

	Designation	Units	Operating range	Data source
Mass flow of supplied fuel	$u_1(t)$	kg/h	150 ÷ 350	PC computation
Volume flow of secondary air	$u_2(t)$	m_N^3/h	0 ÷ 2400	PC
Position of recirculation damper (0 % means closed)	$u_3(t)$	%	0 ÷ 100	PC
Temperature of heating water	$y_1(t)$	˚C	70 ÷ 90	PC
Temperature of flue gas in combustion chamber	$y_2(t)$	˚C	max. 950	PC, thermocouple
Concentration of O_2 in flue gas	$y_3(t)$	%	5 ÷ 15	Flue gas analyzer

4. Model Development and Verification

Model of biomass combustion unit was developed along with more and more experiences from its real operations. In accordance with Table 1, dynamic behaviour of the system is described using three $u(t)$ input quantities and three $y(t)$ output quantities. System was divided into blocks. Relations between quantities were defined using block connection with linear and non-linear description. Transfer functions were employed in linear description while static characteristics obtained via balance modeling were employed in non-linear description.

Response of temperature of heating water $y_1(t)$ to fuel flow $u_1(t)$ increasing is an essential part of the model. Final transfer function describing this dependency goes as follows:

$$G_1(s) = \frac{0{,}0615}{(200s+1)^4} \cdot e^{-480s} \tag{1}$$

Model was created in Matlab/Simulink software and verified by repeated comparison with experimental data. The response of the output variable to 30% step input of fuel is shown in fig. 2.

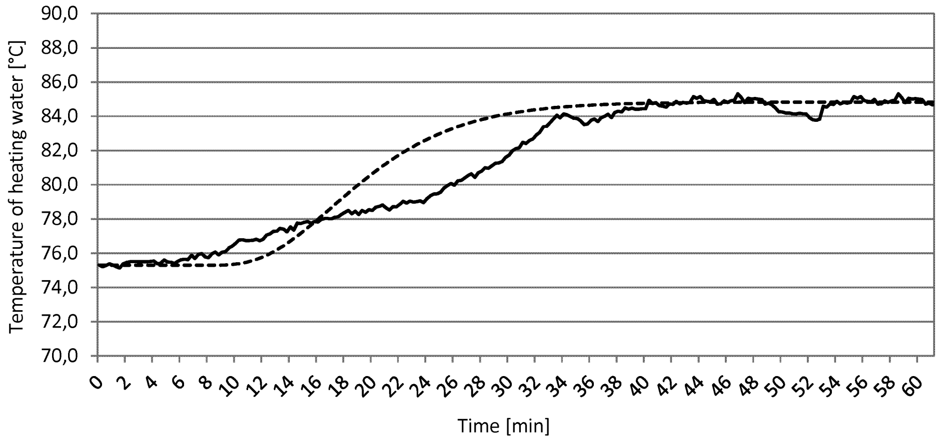

Figure 2: Comparison of simulation results (dash curve) with real response (continuous curve) of heating water temperature $y_1(t)$ to step increase of fuel flow $u_1(t)$

It is obvious that stabilized values of these characteristics basically correspond. Real measuring presents less smooth curve. This is influenced by non-homogenic fuel with steeper curve corresponding to fuel dosage with lower moisture content and therefore better heating value. Created and programmed model was further used for designing of control system.

5. Control System Design

Proper unit functioning requires the control system to secure:

- control of boiler output according to heating water temperature,
- operation of secondary air flow according to temperature of flue gas in combustion chamber,
- operation of flue gas recirculation according to temperature of flue gas in combustion chamber.

Control of boiler output according to heating water temperature presents core task of the unit control. Experiments showed that main controlled quantity, i.e. heating water temperature $y_1(t)$ is influenced only by mass flow of fuel $u_1(t)$; therefore control quality of heating water temperature $y_1(t)$ secured by $G_R(s)$ controller may be assessed independent of other quantities in the system.
PID controller $G_R(s)$ in conventional feedback loop was implemented into the system. Thanks to good knowledge of controlled plant, *Ziegler-Nichols step response method* (Warnick and Rees, 1988) was applied for controller setting. Transfer function $G_R(s)$ goes as follows:

$$G_R(s) = 72{,}3 \cdot \left(1 + \frac{1}{510s} + 472{,}5s\right) \tag{2}$$

Test signal for verification of designed control was a step of required heating water temperature (2 °C). Results of simulation calculation are presented in fig. 3 (dash curve).

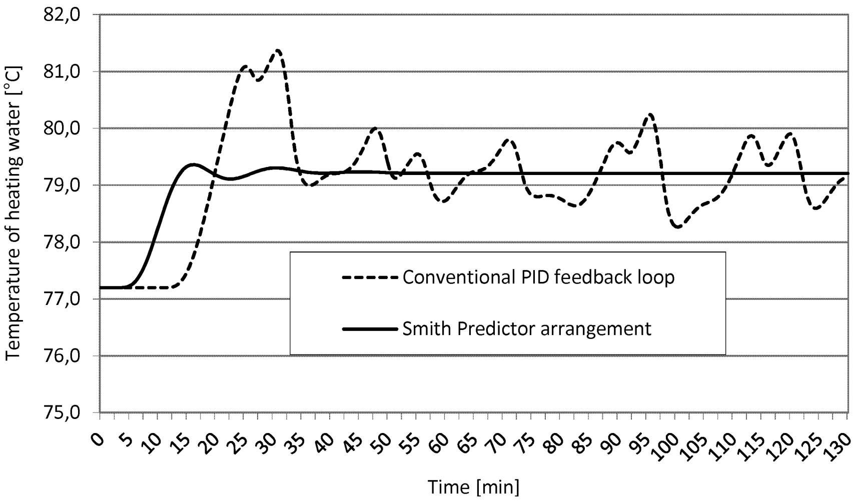

Figure 3: Course of controlled variable (temperature of heating water) during increase of required heating water temperature and subsequent control arrangements

It is obvious that the designed control circuit did not manage to stabilize the controlled $y_1(t)$ quantity and the reason is in significant T_d time delay of biomass boiler (480 s measured). Therefore, adjustment of control system was necessary. In order to eliminate impact of time delay, the arrangement called *Smith Predictor* (Datta et al., 2000) was used. This type of arrangement involves model of plant in control circuit and resulted in stabilizing the controlling (fig. 3, continuous curve).

6. Conclusion

Model was created using suitable combination of balance calculation and extensive experimental measuring. Paper presents procedure of compiling a dynamic model of the system in the area of medium output energy boilers, which resulted in first ever model involving all important non-linear characteristics of the system and describing behaviour of the boiler in all of its operations. Simulation proved similarities of the model and real technologies and revealed substantial flaw of the biomass boilers, i.e. time delay of fuel supply.

Model of control system with new structure was designed, which enabled stabilization of the control. Thanks to high accuracy of the model, we may assume that implementation of these adjustments into real control systems will produce constant control with better dynamics.

Results also want to contribute to theory of modeling and system identification. It efficiently combines analytical and experimental identification approaches in executing a totally new task and thus creates methodological framework for construction of dynamic model of other technologies and industrial processes. Contribution of the work to control theory is mostly linked to new possibilities of control design for systems with poor dynamics and/or high time delay.

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