Boriouchkine, Alexander; Zakharov, Alexey; Jämsä-Jounela, Sirkka-Liisa

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Alexandre Boriouchkine *, Alexey Zakharov,** Sirkka-Liisa Jämsä-Jounela ***

* Aalto University, School of Science and Technology, Department of Biotechnology and Chemical Technology, Process Automation Research Group, 00076 Aalto, Finland. e-mail: aboriouc@cc.hut.fi (corresponding author, phone: +358-9-470 23178).
** Aalto University, School of Science and Technology, Department of Biotechnology and Chemical Technology, Process Automation Research Group, 00076 Aalto, Finland. e-mail: zakharov@cc.hut.fi
*** Aalto University, School of Science and Technology, Department of Biotechnology and Chemical Technology, Process Automation Research Group, 00076 Aalto, Finland. e-mail: sirkka-l@tkk.fi

Abstract: This paper considers the utilization of first principle models of a BioGrate boiler in a disturbance analysis study. The study focuses on the effect of fuel moisture content on the fuel combustion, since it is the most significant disturbance source in the boiler operation. The dynamic model of a BioGrate boiler, upon which the study is based, is heterogeneous, including solid and gas phases. Furthermore, the model considers chemical reactions in both gas and solid phases. In addition, fuel movement on the grate is included into the model. The energy required by the process is employed through a radiation function validated by industrial data. The model is implemented in a MATLAB environment and tested with industrial data. The results are presented and discussed.

Keywords: Power generation, Dynamic modelling, Biotechnology, Finite difference method, Renewable energy systems, System Identification

1. INTRODUCTION

The increasing utilization of renewable energy has created new energy efficiency challenges for industry. As biomass is one of the most important raw materials for renewable energy, all available biomass sources must be considered for energy production. However, the fuel properties of biomass tend to vary significantly depending, for example, on its origin, fuel processing and handling. Variable properties cause large fluctuations in combustion and thus, set challenges for an existing control strategy to keep the process within its constraints.

One of the latest successful processes developed, which uses wood waste as a fuel, is BioGrate-boiler technology, developed by MW Biopower. The combustion of wood waste is a very complex process involving several highly coupled chemical reactions. Furthermore, the operational conditions of the furnace greatly affect the yields of chemicals produced during the combustion process, i.e., fractions of tars, gases and char. Moreover, not only do the yields of chemicals differ under various combustion conditions, their reactivity in succeeding reactions also differ. In addition, significantly varying moisture content causes significant disturbance in the boiler operation. Fuel containing high amounts of moisture can occasionally cause a dramatic drop in a power production. These moisture-induced drops in power production are sometimes confused with a decrease in power production caused by a shortage of fuel in the boiler furnace. Since these two cases cannot be distinguished from each other quick enough, drops in power production are usually treated by adding more fuel. In the case of a fuel shortage, the added fuel would bring the process back to the specified operation conditions; nevertheless, in the case of increased fuel moisture, fuel addition causes an unexpected effect. The added fresh fuel will first continue to decrease the amount of produced heat and electricity, since fuel drying requires a significant amount of energy. After the fuel has dried it ignites and, consequently, raises the temperature of the flue gases causing an uncontrolled increase in steam production as a result. Finally, the unstable steam production leads to a turbine trip and thus financial losses due to unmet power production targets. Furthermore, the disturbances caused by the variation of the moisture content have a delayed impact on the operation of the boiler. Detecting an early disturbance can thus significantly improve the operation of the boiler.

This paper studies the detection of disturbances in boiler operation and is organized as follows: Section 2 describes the structure of a BioGrate boiler process; Section 3 presents the model and its aspects; and Section 4 studies the effect of moisture content on the combustion process. Section 5 presents a possible approach for the moisture content estimation. Section 6 summarizes the results.

2. PROCESS DESCRIPTION OF A BIOGRATE BOILER

A BioGrate consists of the following functional parts: a water filled ash space below the grate which, in turn, is located above the reservoir. The BioGrate is covered with a heat insulating refractory walls (combustion chamber) which reflects the heat radiation back to the grate Anon (2009).

The grate consists of several ring zones, which are further divided into two types of rings: rotating and fixed. Half of the grate rings rotate while the rest are fixed. Every second
rotating ring rotates clockwise and the others anticlockwise. This structure helps spreading fuel evenly upon the surface of the conical grate Anon (2009).

Fuel is fed into the centre of the grate from below. The fuel dries in the centre of the cone as a result of heat radiation, which is emitted by the combusting flue gas and reflected back to the grate by the grate walls. The dry fuel then proceeds to the outer shell of the grate where pyrolysis char gasification and combustion occur. The ash and carbon residues fall off the edge of the grate into the water-filled ash pit Anon (2009).

The air required in gasification and combustion is fed into the grate through the grate nozzles from the bottom of the grate (primary air) and through the nozzles of the combustion chamber (secondary air). In addition, in order to ensure clean combustion, additional air can be fed through the nozzles of the top of the combustion chamber (tertiary air) and the boiler walls. Burning produces heat that is absorbed in several steps. First, the evaporator absorbs the energy of the flue gases. Next, part of the energy of the flue gases is transferred to superheaters. In the third phase, the heat is transferred to the convective evaporator. Finally, economizers remove the remaining flue-gas energy Anon (2009).

The operation principle of a power plant is based on steam generation. As with any other bio power plant, a BioGrate power plant comprises a boiler, a turbine generator, a feed-water tank, a water treatment plant and a flue gas-cleaning system. Solid fuel is fed into the furnace of the boiler where it is combusted to generate heat and flue gases. As the flue gases contain fly ash which contains several harmful components, they are purified of the fly ash before being released into the atmosphere. The heat acquired from the fuel is then used for steam production.

The steam produced in the boiler is led to a generator turbine, which converts its mechanical energy into electricity. The steam pressure decreases as it performs the mechanical work; steam with decreased pressure, is then used to heat utility streams such as water Kiameh (2002). After the steam has released enough energy it condenses, condensed steam called a condensate which along with the pre-treated feed water, is fed into a feed-water tank. Inside the tank, liquid is heated with the bled steam from the turbine. This procedure increases the energetic efficiency of the process Kiameh (2002).

3. THE DYNAMIC MODEL OF A BIOGRATE BOILER AND ITS IMPLEMENTATION IN THE SIMULATION ENVIRONMENT

The current model of a BioGrate, which is utilized in the study, uses a walking grate concept modified for a BioGrate furnace. In addition, the chemical reaction kinetics were specially selected to fit the operational conditions of the BioGrate. Furthermore, an experimental model was used to model the radiation distribution inside the furnace.

The biomass bed reacts in a series of four different chemical reactions: drying, pyrolysis, char gasification and char combustion Peters and Bruch (2001). Active drying starts when the temperature of a particle reaches the boiling point of water. The high temperature of a furnace then initiates a pyrolysis reaction; which, in turn, produces three products: gases, char and tar. The gases are mainly composed of CO, CO₂, H₂, H₂O and C₁-C₃ hydrocarbons. Tar contains many organic components such as levoglucosan, furfural, furan derivatives and phenolic compounds Di Blasi (1996). Next, the model will be discussed in detail.

3.1 Assumptions

Several assumptions were made to simplify the modelling work and are listed in descending order of importance:

1. The system is one dimensional because the length of the grate is significantly longer than its height. Therefore, the temperature gradient in the horizontal direction is insignificant compared to that in the vertical direction.


3. The solid is assumed to be a porous material Yang et al. (2003).

4. Diffusion in the gas phase is neglected, since the effect of convection on the transportation of the gas is significantly greater Peters and Bruch (2001).

5. Pressure dynamics are ignored because the release of gaseous species is negligible compared to the primary air flow; as a result, pressure evolution can be neglected Zhou et al. (2005).

6. Heat produced in char combustion is assumed to be retained in the solid phase Zhou et al. (2005).


8. The temperature of the gas released from the solids is the same as that of the solids Zhou et al. (2005)

9. The temperature of the solids in a discretized block is uniform Zhou et al. (2005).

10. The heat capacity of the wood is assumed to be constant Kær (2005).

11. No heat loss.

Next, the simplified continuity equations are presented.

3.2 Solid phase continuity equation

The solid phase reacts through drying, pyrolysis and char combustion reactions:

$$\frac{\partial \rho_s}{\partial t} = -R_s,$$

where $\rho_s$ is the density of the solid phase, and $R_s$ the overall reaction rate of the solid.

3.3 Energy continuity equation of the solid phase
The energy equation for the solid phase considers heat conduction; heat exchange between the phases; energy lost in the drying and pyrolysis reactions; and energy gained in char combustion:

\[
\frac{\partial T_s}{\partial t} + C_v \rho_s \left( \frac{\partial T_s}{\partial x} \right) = k_{\text{cond}} \left( T_s - T_f \right) + k_{\text{conv}} v_p (T_f - T_s) - \ldots
\]

\[
R_{\text{e}} \Delta H_{\text{e}} = R_{\text{pyr}} \Delta H_{\text{pyr}} + R_{\text{comb, CO}} \Delta H_{\text{comb, CO}} - \ldots
\]

\[
R_{gasi, CO_2} \Delta H_{\text{gasi, CO}_2} = R_{\text{gasi, H}_2O} \Delta H_{\text{gasi, H}_2O}
\]

where \( T_s \) is the temperature of the solid phase; \( C_v \) the heat capacity of the solid phase; \( \rho_s \) the density of the solid phase; \( x \) the vertical coordinate; \( k_{\text{cond}} \) the heat conduction coefficient of the solid phase; \( k_{\text{conv}} \) the heat convection coefficient between the gas and solid phases; \( v_p \) the gas flow velocity; \( T_f \) the temperature of the gas phase; and \( T_s \) the temperature of the solid phase.

3.6 Chemical reactions of the model

The thermal decomposition of wood comprises three main chemical reactions: drying, pyrolysis and char gasification with char combustion. In general, the chemical reactions can be depicted using experimental or semi-experimental models. However, since Arrhenius dependence equations are simple to use and are also accurate, they have been used in this work.

3.7 Moisture evaporation

Typically, solid fuels used in power production contain moisture. Depending on the type of fuel, a fuel particle can contain various amounts of moisture. According to Thummann et al. (2004), fuel particles can contain up to 60 wt. % of moisture while char residue can be as low as 10 wt. % of the wet wood. Water can be bound to the structure of a wood particle or reside in its pores. The drying model used in the current model is after Di Blasi et al. (2003).

3.8 Pyrolysis

After a particle has dried, the next reaction to occur is pyrolysis. In the pyrolysis reaction, a dry wood particle is decomposed into tar, volatile organic components and char. However, fractions of tar, gas and char in the product yield are strongly dependent on the reaction conditions of the combustion process. The current pyrolysis model is based on a study by Alves and Figueiredo (1989).

3.9 Combustion of pyrolysis gases

The yield of pyrolytic gases is around 85 wt. % under the operation conditions of a BioGrate boiler, since under these conditions the gasifying pyrolysis is the dominant pyrolysis mode. Therefore, a significant amount of energy used by the boiler comes from the combustion of gases; this fact indicates that the combustion of pyrolytic gases is the most important energy source. However, the composition of the gaseous products of pyrolysis, reported in Dupont et al (2009), suggests that carbon monoxide has the highest concentration in the pyrolytic gas, while the fraction of other combustible gases remains under 10 wt. %. Therefore, in order to ensure the acceptable accuracy of the model, while keeping the model simple, only the oxidation of carbon monoxide to carbon dioxide is considered. In addition to the oxidation of carbon monoxide, the combustion of hydrogen is also included in the model. Reaction rates of gas combustion reactions used in the model are presented in the study of Babushik and Daidancha (1993).

3.10 Char conversion reactions

Char combustion in the model is based on that presented in Senneca (2007). This model was chosen because it is valid over the temperature range 440-800°C, which corresponds to the temperature of char combustion in a BioGrate. The
gasification reaction of char with carbon dioxide is based on kinetics reported by Senneca (2007).

3.11 Implementation of the dynamic model

The model was implemented in the MATLAB environment, in which a set of finite difference methods was used to solve the continuity equations. The overall solving algorithm is presented in Fig. 1.

4. THE EFFECT OF FUEL MOISTURE CONTENT ON THE FUEL COMBUSTION

In order to evaluate the effect of moisture on the overall combustion process, a simulation with varying moisture content is conducted. The simulation considers a moisture content variation in a form of step changes. The moisture content function included a step of 200 samples describing the moisture content of 45 wt. %, while the second step was 200 samples long representing a moisture content increase to 70 wt. %, and the nominal value of the function remains at 60 wt. %. The dynamic model was simulated for 2000 samples, during the simulation the first step started at the time period of 200 samples and returned to nominal value at the time period of 400 samples. The second step was introduced at the time interval of 500 through 700 samples.

The simulation shows that the decrease in the moisture content increased the surface temperature of the fuel layer almost immediately. However, the introduced moisture content increase started to decrease the surface temperature around 550 samples, nevertheless the ignition of drier fuel increased the mean surface temperature by 10 K despite the increased moisture content in fuel. Nevertheless, at the time point of 950 samples the increased moisture content decreased the surface temperature by 10 K. The mean gas temperature resembles the behaviour of the mean surface temperature, however, after the ignition moist fuel started to increase the mean temperature of the gas. This is a result of water steam reaction with the char which produces hydrogen. Increased moisture content increased the production of steam, which in turn, increased the reaction rate of char with the steam and, consequently, the production of hydrogen. While combusted, the hydrogen releases significant amounts of energy, thus, increasing the temperature of flue gases. However, despite the increased amount of reacting char the production of carbon monoxide decreases. This is the consequence of delayed pyrolysis, since the drying of moist fuel requires a longer time and delays the initiation of the pyrolysis. Furthermore, the increased moisture content decreases maximum gas temperature significantly along with the amount of produced flue gases. This decrease causes large fluctuations in the power production of the boiler. Fig. 2 presents the form of moisture content step function along with gas flows and maximum gas and solid temperatures while Fig 3 depicts mean surface and gas temperatures.

5. AN EXAMPLE FOR THE ESTIMATION OF THE MOISTURE CONTENT

This section proposes an example and a preliminary study on how the moisture content of the fuel can be estimated. This approach is based on system identification utilizing both a linear and a nonlinear model. The models are identified from three variables, which are usually measured at the power
plant: oxygen content, flue gas flow and flue gas temperature. These variables are then simulated with a dynamic model for 2,000 samples with varying moisture content at a point 1.5 m from the center of the grate. This point corresponds to 0.5 m² of the overall grate area. The first 700 samples are used for the model identification of both an ARMAX and a nonlinear ARX model. The identified models are then validated using the whole dataset. In addition, another 2,000 samples are generated to validate the models with an altered fuel moisture content; in addition, a random variation of moisture content is introduced at the period of 700-1,100 samples. The moisture content of the fuel is generated with a sum of sinusoidal signals. The data set used for the model identification is presented in Fig. 4, while Fig. 5 presents the second data set used for model validation. The data was normalized prior to the identification procedure. Both models are identified using the MATLAB system identification toolbox.

The identified ARMAX model has the following structure:
\[ A(q)y(k) = B(q)u(k) - n_k) + C(q)e(k) \]
where the order of polynomial \( A(q) \) is 2, \( B(q) \) is 4 and \( C(q) \) is 5 while \( n_k = 100 \) samples.

The nonlinear ARX model utilizes a wavelet network with one unit to describe the nonlinear terms of the model while the current model output is a function of two previous inputs and outputs.

The simulation results show that both models accurately predict the moisture content of the first dataset based on the flue gas flow, the temperature of the flue gas and the oxygen content. Although the ARMAX model is accurate, the nonlinear model exhibits better accuracy of the prediction, since not all relationships between inputs and outputs can be captured from the dynamic model. The simulation results of the first dataset for the identified ARMAX and nonlinear ARX models are presented in Fig. 6. For convenience, the figures present every fifth data sample instead of every sample.

In order to evaluate the accuracy of the identified model, a different pattern of moisture variation with another 2,000 samples was generated with the dynamic model. The results show that with the second data set, the linear model is significantly less accurate than the nonlinear one. This is especially so at the time period between 700-1,100 samples, at which an additional disturbance is introduced and the linear model fails to predict the moisture content of the fuel. These results suggest that moisture content estimation requires a nonlinear model, since the linear model is not able to capture all the relations between the input and output.
variables. The simulation results for the ARMAX and the nARX models are given in Fig. 7.

![Graph](image_url)

**Fig. 7.** Simulation results of the ARMAX and the nARX models with the data set generated with the second data set.

6. CONCLUSIONS

To summarize, the moisture content affects the combustion process significantly; therefore, it is important to detect the changes in moisture content as early as possible. The paper presented a possible approach for the moisture content estimation using linear and nonlinear models identified from the process data. The linear model failed to predict the moisture content when a significant disturbance was introduced, mainly due to the nonlinearity of the reactions and the heat transfer involved in wood combustion. In contrast to the linear model, the nonlinear model exhibited a better accuracy. Nevertheless, the study showed that moisture content could easily be estimated from the measurements available at the plant. However, further study requires evaluating the accuracy of the black box models under the changed operation conditions of the boiler, since in the presented simulations operation point of the boiler was assumed to be constant. Particularly, the combustion air feed was kept constant, however, in practice the volumetric air feed is not a constant. In addition to the air feed, many other variables, assumed in this study as constants, can, in practice, exhibit significant variations. Therefore, since the mechanistic models are typically valid under the changed operation point, it is highly motivated to simplify the dynamic model of a BioGrate boiler for the moisture content estimation.

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