Biomass combustion for power generation: Dynamic modeling and full-scale industrial experiments

Alexandre Boriouchkine
Aalto University, School of Chemical Technology, Process Control and Automation Research Group, P.O. Box 16100, 00076 Aalto, Finland, alexandre.boriouchkine@aalto.fi

Alexey Zakharov
Aalto University, School of Chemical Technology, Process Control and Automation Research Group, P.O. Box 16100, 00076 Aalto, Finland, alexey.zakharov@aalto.fi

Juha Huotari
MW Power Oy, Rautpohjankatu 1, 40700 Jyväskylä, Finland e-mail: juha.huotari@mwpower.fi

Sirkka-Liisa Jämsä-Jounela
Aalto University, School of Chemical Technology, Process Control and Automation Research Group, P.O. Box 16100, 00076 Aalto, Finland, sirkka-liisa.jamsa-jounela@aalto.fi

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ABSTRACT

This study analyzes boiler dynamics and the effects of different fuel types on boiler operation. The dynamic BioGrate boiler model used is heterogeneous, which includes both solid and gas phases. In addition, the model considers chemical reactions in both the gas and solid phases, fuel movement, and primary air distribution on the grate is also included in the model. The incident thermal radiation falling on the bed from the refractory wall is described by an experimental radiation function validated with industrial data. Full scale industrial tests were performed to validate the dynamic mechanistic model of the grate boiler. During the changes in fuel type, the dynamic response of the boiler and the combustion behavior of the fuel bed were monitored. In this paper, the observed results are presented and compared with the model predictions and finally analyzed for a better understanding of biomass combustion on conical grates.

1 INTRODUCTION

Legislation supporting sustainable development is forcing industry to increase the share of electricity and heating power produced from renewable fuels. Consequently, the combustion of biomass is increasingly attracting the attention of industry. The EU directive 2009/28/EC on the promotion of renewable energy states that 20 % of all energy used by the EU member states must originate from renewable sources by the year 2020. Moreover, the directive emphasizes the importance of decentralized energy production from local renewable sources by small and mid-sized enterprises. However, efficient utilization of renewable energy sources poses several challenges. These shortcomings are the result of significant variations in the quality of the biofuels used.

Numerous works have addressed combustion dynamics and behavior in a packed bed by using numerical simulations and laboratory experiments. Ground-breaking work in this field includes studies on lignosellulosic biomass combustion by Shin and Choi (2000), Saastamoinen et al. (2000), Goh et al. (2000), Goh et al. (2001), van der Lans (2000), 0 et al. (2002) and Yang et al. (2003). More recent studies by Zhou et al. (2005), Kær (2005), Asthana et al. (2010), and Boriouchkine et al. (2012) provide information on the combustion characteristics of straw, municipal solid waste (MSW), and woody biomass.

This study analyzes combustion dynamics in a conical grate boiler which can utilize solid fuel with a moisture content of up to 65 w%. The paper presents the validation of the dynamic, mechanistic model of a conical grate boiler against the industrial data in terms of the fuel combustion rate. The paper is structured as follows: Section 2 presents the process description, Section 3 describes the dynamic model of a conical grate boiler, Section 4 presents the experimental setup, model validation and simulation results. Finally, Section 5 summarizes the findings.

2 PROCESS DESCRIPTION

BioGrate boilers utilizes conical grate technology provided by MW Power Oy. A BioGrate consists of the following functional parts: grate rings, a refractory wall and a water-filled ash space below the grate. To improve fuel spreading in the combustion chamber, the grate consists of several ring zones, which are further divided into two types of rings: rotating and fixed. Half of the rotating rings rotate clockwise, the rest counterclockwise. The fixed rings are located between the rotating rings. The heat-insulating refractory walls surround the combustion chamber formed by the grate rings. Fuel is fed into the center of the grate from below. The ash and carbon residues fall off the edge of the grate into the water-filled annular ash space.

3 Description of the dynamic model of the BioGrate furnace

The model describes the combustion of solid biomass in a BioGrate boiler. The model comprises two phases: the gaseous and the solid one. In the solid phase, the fuel goes through drying, pyrolysis, char oxidation and through char gasification reactions with CO_2 and H_2O. The energy equation for the solid phase describes heat conduction, heat exchange between the phases, energy lost in the drying and pyrolysis reactions, and energy gained in char combustion. The gas phase continuity equation accounts for the reacted solid matter which is transferred into the gas phase and for the gas flow. The gas phase consists of the following components: water vapor, oxygen, carbon monoxide, carbon dioxide, nitrogen, and hydrogen. The energy continuity equation of the gas phase considers the heat exchange between the gas and solid phases, the energy received through gas convection, and the energy gained through carbon monoxide and hydrogen oxidation.

The solution algorithm of the model is presented in Figure 1. A more detailed description of the dynamic model is provided in Boriouchkine et al. (2012).

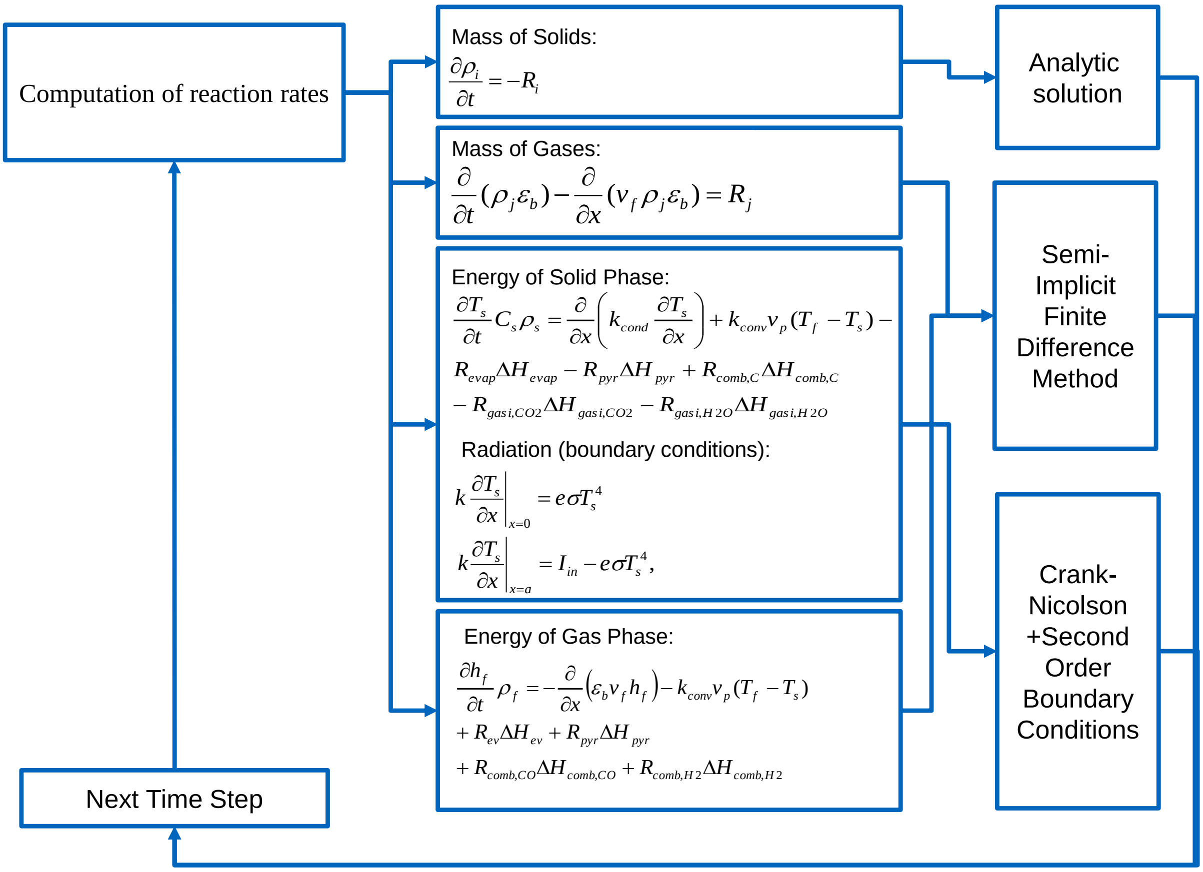


Figure 1 The overall solution procedure of the model

4 RESULTS

This section first presents the validation of the developed BioGrate model which is then followed by simulations of fuel combustion with two different moisture contents, 55 w%, for typical fuel and, 20 w%, for dry fuel.

4.1 Dynamic model validation

The model was validated with measurement data obtained during industrial tests at a BioGrate boiler site. Tests included three changes in moisture content which were induced by using three batches of fuel with different volumes and the moisture content of 20 w%. The volumes of the first, second, and third batches were 5, 10, and 25 m^3, respectively. In all of the tests, the power output of the boiler was kept constant at approximately 16 MW.

The model validation was performed by comparing the combustion rate calculated from the process data which was obtained during the industrial experiments to the one predicted by the model. The combustion rate from the process data was computed by using the measured air supply rate and the flue gas oxygen content. In addition, a FTIR sensor, Servomex 2000, was installed to measure the flue gas moisture content to avoid the bias in computations due to dilution of the actual O_2 measurement by evaporated fuel moisture.

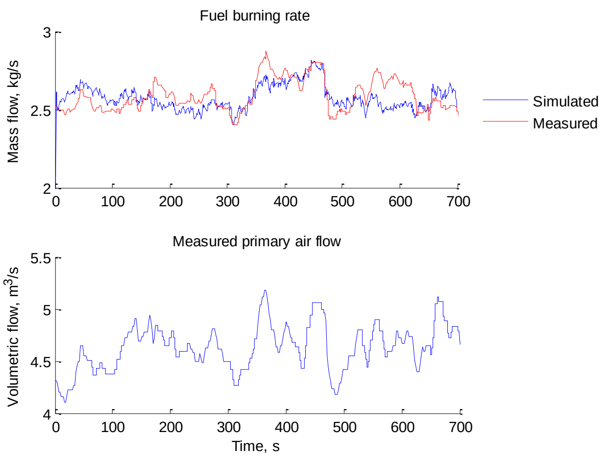


Figure 2 Fuel combustion rate comparison (top) and primary air flow used for the model validation (bottom).

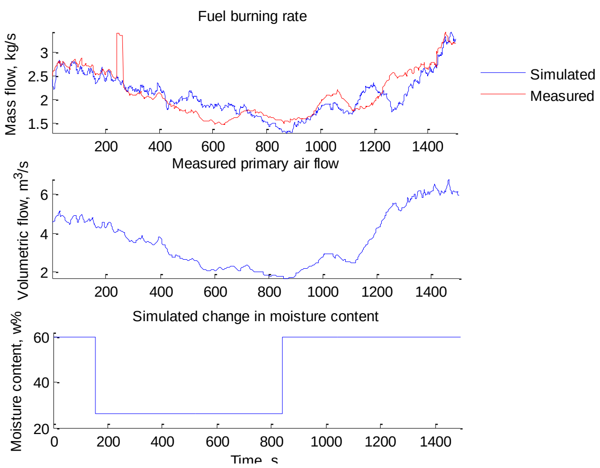


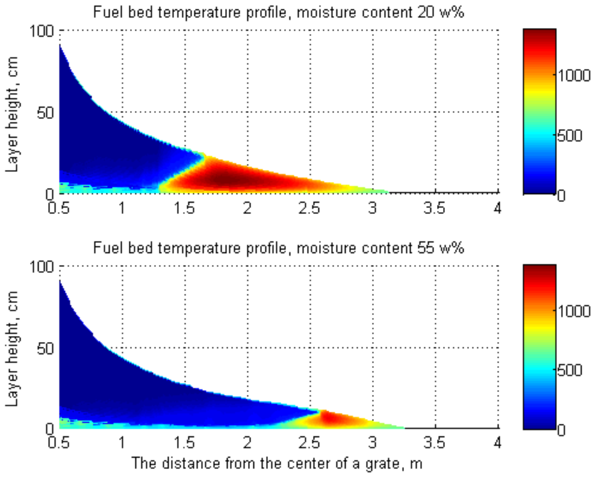
Figure 3 Fuel combustion comparison (top), primary air flow (middle), and the simulated step change in moisture content (bottom).

The dynamic model, presented in Figure 1 was validated with two simulations. First, a steady furnace operation was simulated to evaluate the model response to a change in the air supply while the fuel input remained constant. Next, a step change in the fuel moisture content was introduced to reproduce the industrial test in which 5 m^3 of dry fuel was fed to the boiler. Both simulations utilize primary air flow values measured during the experiments. The performance of the model was evaluated in terms of burned fuel. The steady state performance is presented in Figure 2 while the dynamic test is demonstrated in Figure 3. Results indicate that the model was able to predict the amount of burnt fuel in both steady state and dynamic test.

4.2 Simulation results

4.2.1 Temperature distribution of the fuel layer

The temperature profile of a typical bed, presented in Figure 4, indicates that the fuel undergoes devolatilization and finally ignites as it spreads towards the outer ring. A narrow combustion front can be observed on the surface of the bed which is a result of incoming heat radiation. This result is also supported by the visual observations of the burning bed, where no active burning was observed on the surface. The temperature profile of the dry fuel, presented in Figure 4, shows that temperatures inside the bed are higher than with the typical fuel. In addition, dry fuel ignites much faster, since combustion front reaches the surface already at 1.2 m from the center. Furthermore, the temperature measurements obtained during the experiments and the simulated temperature profile of the dry fuel suggest that the ignition point inside the layer is located much closer to the center of the grate than with the wet fuel. Likewise, the temperatures of the gas phase, shown in Figure 5, indicate similar tendencies to those of the solid phase, suggesting significantly higher temperatures inside the dry fuel bed than inside the typical one. However, the gas phase temperature is the highest at the combustion front, in contrast to the solid phase which achieves the highest temperature at the char combustion zone.



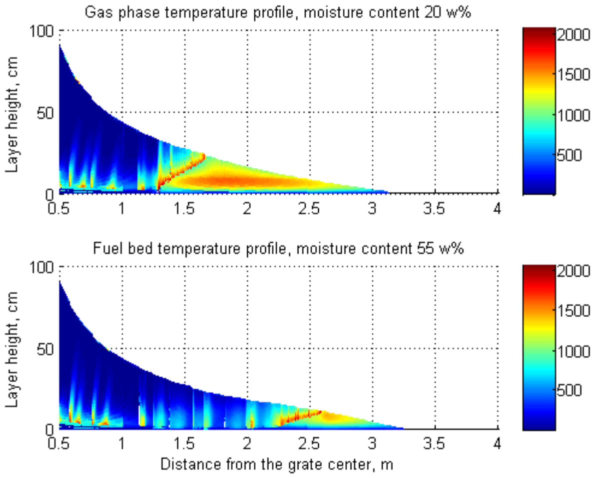


Figure 4 The solid temperature profile of a bed with different initial moisture contents

Figure 5 The gas temperature profile of a bed with different initial moisture contents

4.2.2 Flue gas distribution of the fuel layer

The simulation results suggest that low moisture content allows earlier start of pyrolysis in dry fuel bed than in wet fuel, creating a spike in volatile (C_xH_y) release rate which can be observed in Figure 6. Furthermore, the results shows that in dry fuel, pyrolysis stops 1.6 m away from the grate center, instead, in wet fuel, volatile release ceases 2.6 m away from the center.

After the fuel has been completely pyrolysed, only char is left, which is oxidized to form carbon monoxide and carbon dioxide. The char combustion phase can be observed in Figure 6 as an increase in CO release, which makes carbon monoxide the largest released component. However, because of the oxygen deficiency in the dry fuel bed, due to lower primary air flow, the remaining char takes a relatively long time to combust. In contrast to the situation with dry fuel, the char oxidation of the typical fuel is not limited by oxygen deficiency. The difference in oxygen content is captured well by the gas distribution profile presented in Figure 6 which indicates that the dry fuel layer contains no oxygen in the flue gases.

5 CONCLUSIONS

The model developed for this study has been successfully validated, and it showed a good accuracy. Most importantly, the model was able to follow the trend in combustion behavior during a fuel input change. The simulations showed that fuel with a low initial moisture content fully ignites much earlier than the typical fuel. In addition, due to early ignition, the dry fuel bed contains a larger char quantity than the typical fuel. Therefore, if dry fuel is utilized for power production a larger quantity of air should be fed close to the grate center, as opposed to wet fuel which requires more air at the outer rings of the grate.

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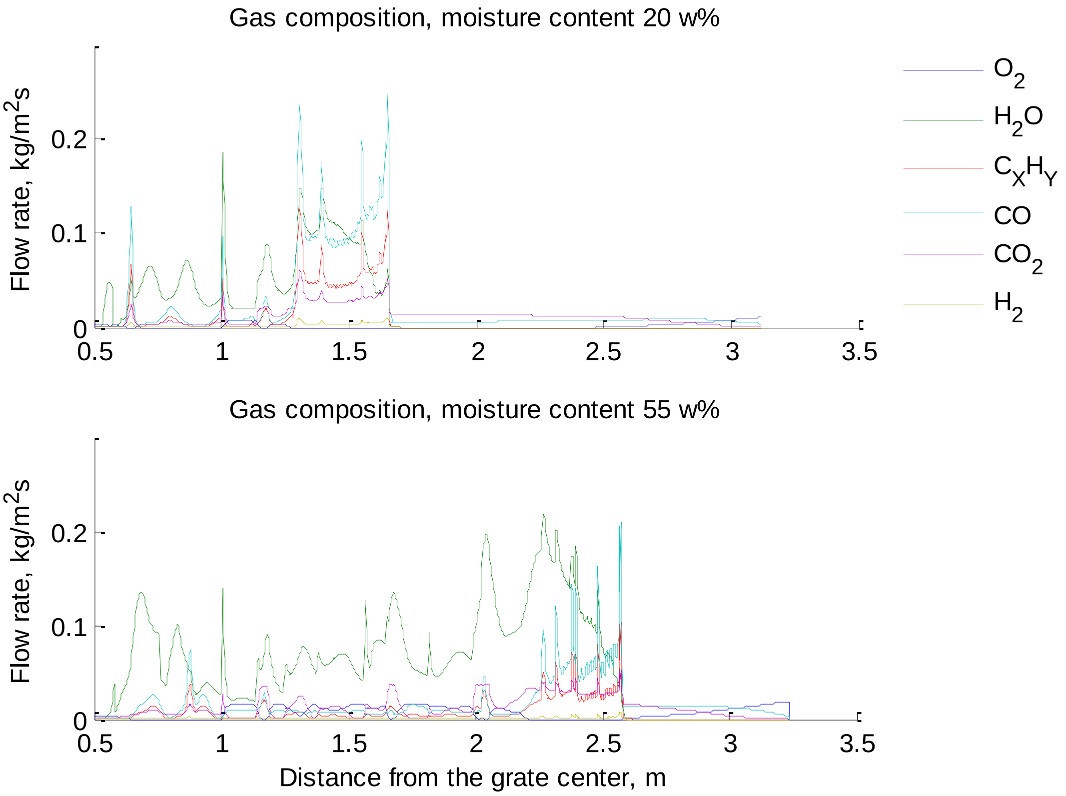

Figure 6 Gas phase composition of a bed with different initial moisture contents

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