Analysis and optimization of a cogeneration system based on biomass combustion.

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Abstract

The most well-proven and commercial available technology for decentralised cogeneration based on biomass combustion is the Organic Rankine Cycle with its main advantages, which are excellent part-load operation and reduced operating costs. The energy supply system of the urban area Scharnhauser Park nearby Stuttgart, Germany is a practical example for the utilization of the ORC technology. The plant is equipped with an 8 MW biomass grate boiler and covers the main part of the heat demand of the area. The installation has a pilot project character and can be used for the investigation of bioenergy appliances based on wood combustion.

The analysis aims to optimize the performance of the combustion process in the biomass furnace at the cogeneration plant. For this purpose a thermodynamic model for the biomass burning process in a grate furnace was developed. The mathematical model describes both, the thermal decomposition of the fuel on the grate as well as the gas phase combustion in the secondary zone. This approach enables calculation of the temperature profiles, gas composition and the combustion stoichiometry at each step of the combustion process. The presented methodology can be used to deal with multivariable interacting processes, multiple conflicting objectives and constrains which are the main problems related to combustion process control in biomass plants.

Keywords

Biomass combustion, grate furnace, renewable cogeneration

Introduction

Biomass already plays a major role in the renewable energy balance and over 90% of energy generated from biomass is produced in biomass furnaces [1], [2]. Among the technologies for energy production from solid biomass, combustion is the most advanced and market-proven application, while pyrolysis and gasification are still in the development stage [3], [23]. Consequently combustion of biomass has been found to be the most promising method for biomass utilisation.

Modern biomass combustion plants and biomass boilers achieve an efficiency of over 90% and utilize sophisticated technology to control the process in order to minimize its environmental effects and promote efficiency [4]. However, there are still unsolved problems related to the complexity of the biomass burning process, which include among others relatively low ash melting temperature or, variation in the fuel properties. Furthermore, efficiency enhancement and economical feasibility of bioenergy projects are often crucial issues [24]. One of the

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problems with using solid biomass as a fuel are the varying fuel parameters like moisture content, calorific value and geometric shape and size [5]. Furthermore, stable combustion of biomass cannot always be achieved due to the fact that the commonly used control strategies are not yet fully optimized [6]. Unstable operation of biomass combustion systems is of the main reasons for problems related to ash slagging and fouling as well as decreased lifetime of combustion equipment [7].

An improved understanding of the influence of the operational parameters on the combustion behaviour of biomass in a grate furnace would be certainly beneficial for achieving of stable working conditions of combustion systems and increasing the thermal power output of biomass combustion appliances [8], [9]. To better understand the complex combustion process occurring in grate boilers mathematical modelling can be used as a tool for analyzing of the influence of fuel parameters and operational settings on the thermal decomposition of the fuel in a grate combustion system [10], [11].

The purpose of the presented work, that started 2007, is the development of a mathematical model for biomass combustion that could be used for model-based optimization of control strategies of grate furnaces. To validate the model, measurements were performed at an 8 MW biomass furnace with inclined moving grate, which serves as the thermal energy source for the cogeneration module at the CHP plant Scharnhauser Park. Consistency between measured values and model predictions is fairly good.

Biomass combustion in a grate furnace

Grate firing is one of the mainly used technologies for biomass combustion as it combines relatively high efficiency with reasonable investment and operating costs. Biomass grate furnaces can deal with varying fuel properties and thus can widely be used as thermal energy source in heat and power generation appliances [12]. In large-scale biomass combustion plants separation of different stages of thermal decomposition of the fuel on the grate as well as staged air combustion are applied. The combustion air supply in the grate zone is divided into sections according to the requirements of the individual steps of thermal decomposition of the fuel on the grate. This complex combustion air management allows smooth operation of grate furnaces at partial load down to the 25% of the nominal load [13]. In modern biomass furnaces staged air combustion is also applied in order to simultaneously reduce both the emissions from incomplete combustion and NO_X emissions. The combustion chamber is divided into a primary and secondary zone. In the primary zone thermal decomposition of fuel on the grate occurs in fuel-rich conditions ($\lambda<1$), where the heat release from the fuel bed is determined by the amount of air fed to the grate zone. Due to the sub-stoichiometric conditions unburned fuel components leave the bed and are transported with the gas flow to the secondary combustion zone [14].

Thermal decomposition of biomass in a grate furnace consists of several interlinking processes of high complexity as shown in Figure 1. After the fuel enters the hot combustion chamber it will be heated by a strong radiation from the furnace walls. Counter current combustion of biomass, where the hot combustion gases flow in the opposite direction to the fuel movement, is the mainly applied solution as it can be used for burning of wet fuels with relatively low heating value. Moisture will be evaporated at a constant temperature of about 100°C in the region of the first part of the grate. After all the moisture will be driven out the fuel temperature rises quickly to 260°C which is the starting point of fuel devolatilisation. Biomass consists in 85% of volatile matter and thus the main fraction of the fuel mass will be released during devolatilisation. During this phase about 70% of the fuel heating value leaves the fuel bed to the region over the grate combustible gas mixture. After all moisture and volatiles have left the fuel bed the final stage of charcoal combustion begins, where approximately 30% of the fuel heating value will be released [15].

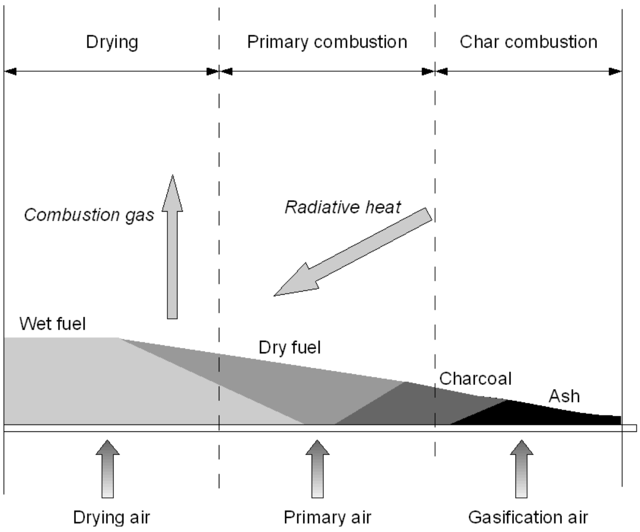

Figure 1: Schematic view of thermal decomposition of biomass in a grate furnace.

The released gases are partly combusted in the region over the grate resulting in a long flame above the grate. For sub-stoichiometric conditions the heat release from the fuel bed is mainly determined by the airflow rate. Due to the fuel-rich combustion conditions in the grate zone large amounts of unburned fuel components leave the bed and have to be burnt afterwards in the secondary combustion chamber where good mixing conditions should be achieved. If good mixing conditions are ascertained the emissions of CO and hydrocarbons from incomplete combustion can be close to zero [16].

Simulation model for biomass combustion in grate furnace

Based on biomass combustion theory, a model for counter current combustion of biomass in a grate furnace will be presented, in which each step of the thermal decomposition of biomass will be analyzed on the basis of energy balance equations. As the chemistry of thermal decomposition reactions during wood combustion is not known in detail, the description of the process has to be simplified for model purposes [17], [18].

The combustion chamber of the analysed furnace was divided into zones according to the individual steps of the biomass burning process (Figure 2). This approach enables an effective description of the biomass combustion process and solution of relevant equations in order to simulate the characteristics of biomass burning in a grate furnace. The thermodynamic model can be used for calculation of temperature profiles, gas composition and the combustion stoichiometry at each step of the combustion process. Therefore, the model can be applied for the evaluation of the influence of control parameters on the heat output of the system. Additionally the developed model can be used to analyse how fuel properties such as moisture content and calorific value influence the thermal decomposition of biomass in the fuel bed.

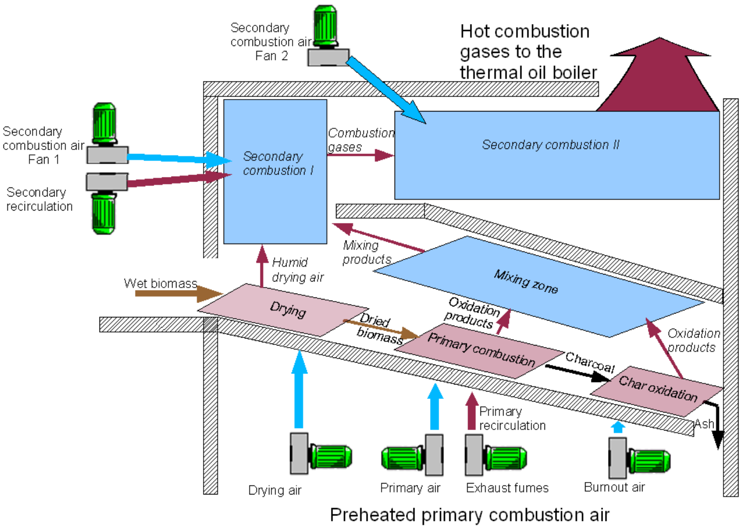

Figure 2: Combustion chamber of the biomass grate boiler.

The simulation model for biomass combustion was developed by using the graphical programming software INSEL. The structure of the model is presented in Figure 3. The biomass combustion process was divided into four main sub-processes: evaporation of moisture from fuel, volatile release during primary combustion, char oxidation and burning of the volatiles during secondary combustion.

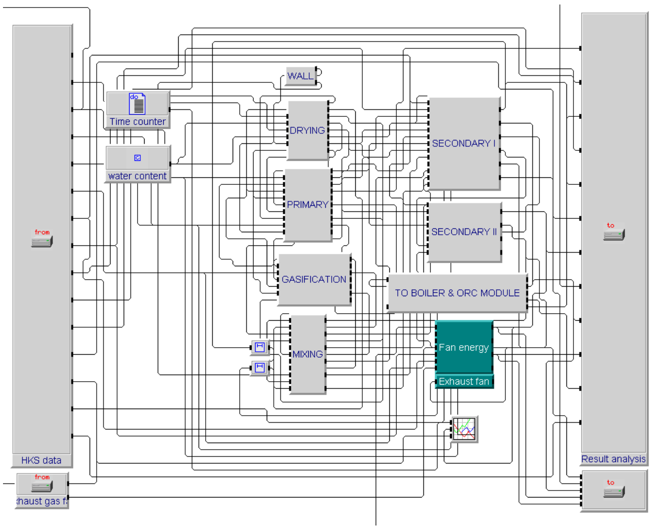

Figure 3: Combustion model structure.

Moisture evaporation

During moisture evaporation the fuel temperature remains around the boiling point due to the endothermic character of the process [19]. The rate of drying is related to the amount of heat provided by the over bed radiation, which is assumed to be the main heat transfer mechanism between the fuel and the hot furnace walls. The fuel is assumed to be dried by over bed radiation at a temperature of 850°C. The moisture released from the fuel bed is transported by the mass exchange between the wet solid and the preheated drying air fed under the grate.

Primary combustion, volatile release

During primary combustion the fuel is thermally decomposed which results in formation of volatiles with varying compounds. The volatiles consist mainly of CO, CO_2, H_2, C_xH_y and other trace compounds [20]. The primary combustion occurs in fuel-rich conditions and the heat of combustion of volatiles is related to the amount of primary air fed to this zone. The primary combustion stage comprises the thermal decomposition of the major portion of the fuel mass and gaseous compounds released during devolatilisation have to be burned afterwards in the secondary combustion zone. In the case of combustion of fuels with lower quality the ash of the fuels contains a lot of impurities and the ash melting temperature of such fuels is considerably lower. Therefore, the temperature in the grate zone should not exceed 900°C for normal operation. Efficient temperature control when burning low quality fuel is achieved by flue gas recirculation where exhaust fumes with relatively low temperature are returned back to the hot combustion chamber to cool the grate and the combustion chamber.

Char oxidation

Biomass consists in about 15% of charcoal and the amount of char burned in the final stage of thermal decomposition of biomass ranges from 20 to 85% of the total char burned [21]. The char oxidation takes place at much slower rate compared to the primary burning stage and comprises about 20% of the combustion time [15]. The reaction of charcoal combustion occurs in oxygen-rich conditions and is limited by the diffusion of oxygen from the combustion air to the particle. The heat released during char combustion is related to the reaction products distribution and can be defined by empirical correlations for the ratio of the product gases CO and CO_2.

Secondary combustion, burning of the volatiles

At the beginning of the secondary combustion zone, secondary air is injected in order to achieve a complete burnout of the combustible gases from the grate zone. The reactions of the secondary combustion are exothermic which results in higher gas temperature. The burning process of the gases is limited mainly by the mixing rate of the gaseous mixture with secondary air. Flue gas recirculation is applied in this zone in order to improve the mixing conditions and to control the temperature of the hot combustion gases [25]. Good mixing of combustion gases with air is additionally achieved by introduction of secondary air jets to assist the mixing. The amount of air needed for complete combustion and can be seen as a fundamental parameter in the definition of thermal efficiency of the appliance [22].

Experimental – measurements

All measurements were conducted at the biomass grate furnace at the CHP plant Scharnhauser Park. The combustion appliance is a typical inclined grate furnace (Figure 4), equipped with three primary air zones (for drying, devolatilisation and char combustion) and a flue gas recirculation system for the primary and secondary zone.

The fuel used was wood chips made of landscape management residues with an average moisture content of 50% and a typical composition for wood (carbon 50%, hydrogen 6%, and oxygen 44%).

Primary and secondary air flows were not directly measured, but determined on the basis of the combustion air fans performance. The temperatures in the secondary and primary zone of the combustion chamber were measured with PT 100 temperature sensors. The oxygen content of the flue gas was measured using amperometric oxygen sensor. The CO content of exhaust fumes was controlled with URAS 14 gas analyzer module in order to ensure complete combustion.

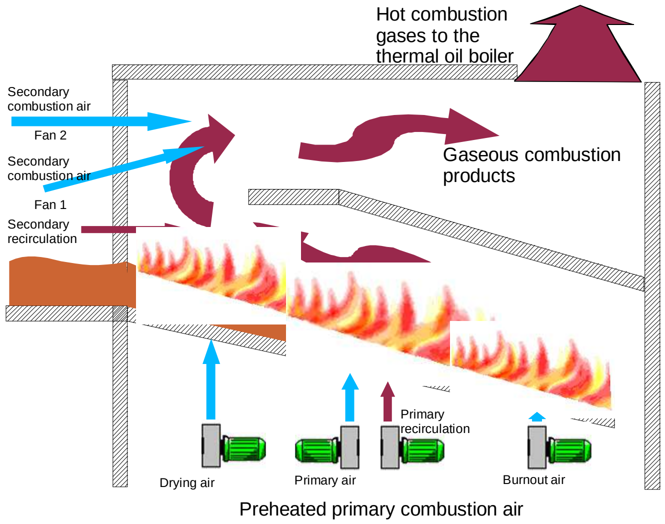

Figure 4: Furnace at the CHP plant Scharnhauser Park.

Model validation

Measurements of the temperature profiles in the combustion chamber and plant performance were carried out in order to validate the model. The major input values for the model are moisture content of the fuel, fuel mass flow, primary and secondary air mass flows and the recirculation rate. Figure 5 shows the comparison of measured and simulated values.

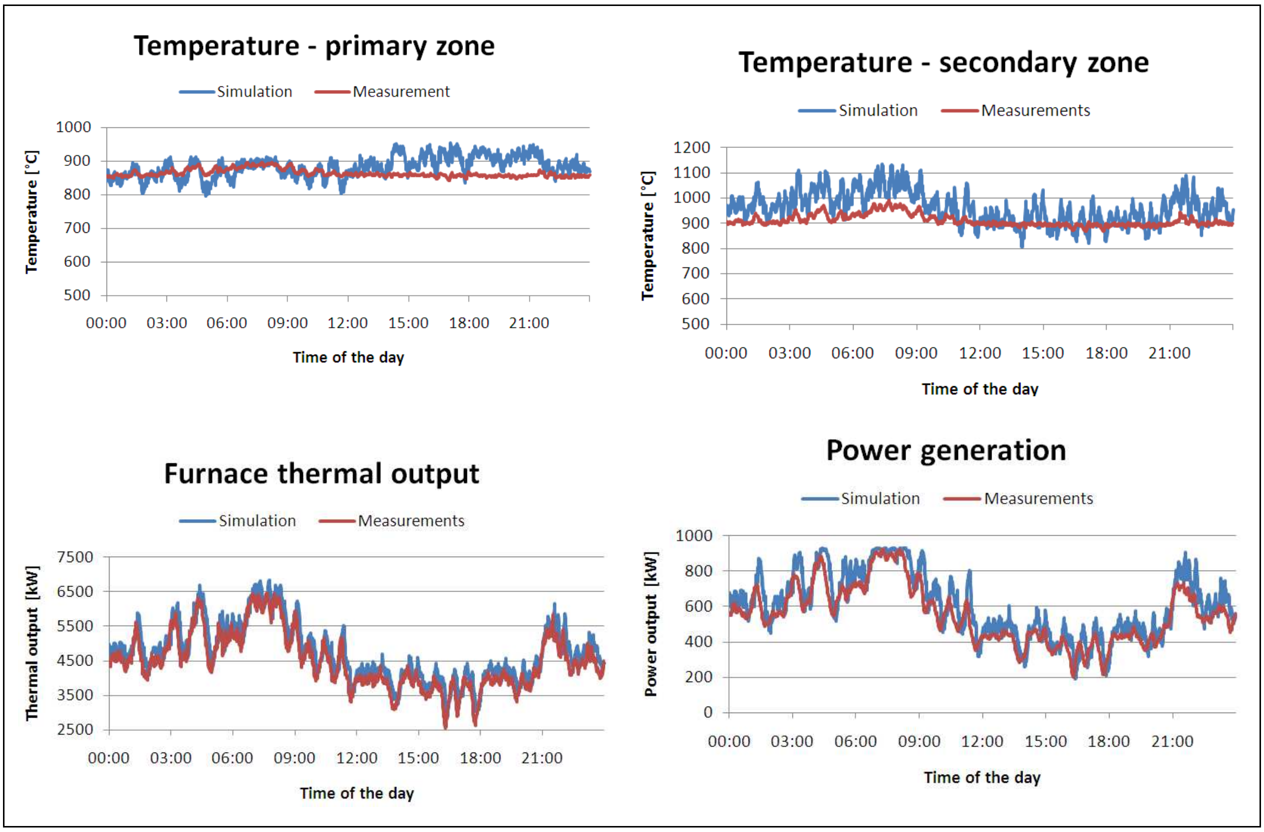

Figure 5: Comparison of simulated and measured values.

The first two charts show temperature profiles in the primary and secondary combustion zone. The third chart shows the performance of the combustion system and the last chart presents a comparison of measured and simulated power generation of the cogeneration module. The measured and simulated values match very well, even though some variations occur due to changing working conditions. According to the presented results it can be stated that the model predicts quite satisfactory the temperatures in the combustion chamber and the biomass cogeneration system performance.

Conclusions

Major motivation for applying simulation models for optimisation of biomass furnace operation is the need to improve the economic feasibility of energy generation based on biomass combustion.

A simplified, but effective model for combustion of biomass in a grate furnace was presented. The model was validated by comparison of simulated and measured values at the biomass grate furnace (8 MW) of the CHP plant Scharnhauser Park. The consistency between measured and simulated values is fairly good.

The mathematical model is based on energy balance equations developed for each of the individual sub-processes of biomass combustion. The solution of the energy balance equations, which have to be fulfilled at each moment of the combustion process, can be used to estimate the influence of control parameters on the performance of the biomass furnace. The presented modelling approach enables to predict the burning characteristics of biomass in a grate furnace and is suitable for model-based control strategies. Model based control strategies enable a systematic way of dealing with multivariable interacting processes, multiple conflicting objectives and constraints, which are the main problems related to combustion process control in biomass plants. Therefore their implementation would lead to a significantly improved control operation performance of biomass combustion appliances.

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