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MODELING OF GRATE COMBUSTION IN AN ORC COGENERATION PLANT

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ABSTRACT: Worldwide biomass ranks fourth as an energy source and over 97% of the generated bio-energy are produced in biomass furnaces. The recent development in biomass combustion technology has led to improvement of efficiency and significant reduction of emissions from modern conversion installations. However, the operation and maintenance of biomass furnaces requires detailed understanding of the complex burning process. There is still a lack of detailed theoretical study and practical experience, which could be used to deal with the difficult combustion characteristics of biomass. In this paper mathematical simulation for the grate combustion of biomass has been carried out. The aim of the work is the development of a process model which could be used for control purposes. The biomass combustion process can be divided into four successive steps: moisture evaporation, pyrolisis, char oxidation and gas combustion. The model is based on governing equations for each stage of the combustion process in an inclined grate furnace, which makes it particularly suitable as a basis for model based control strategies.

1. INTRODUCTION

Biomass already plays a major role in the energy balance in some countries and could be far more intensively used as it has been done so far [1]. Various global energy studies indicate that biomass is available in large quantities and may contribute from 100 to over 400 EJ/a to the global energy supply [2]. Another considerable advantage of biomass is that it is the only renewable energy source that can be stored and thus energy can be produced according to the heat or electricity demand [3].

Among the technologies for energy production from biomass, combustion is the most advanced and market-proven application, while pyrolisis and gasification are still in the development stage [4,5]. Consequently combustion of biomass has been found to be the most promising method for future biomass utilisation. Although biomass combustion is the most mature energy conversion technology there are still unsolved problems related to the complexity of biomass combustion, which include among others relatively low ash melting temperature, variation in the fuel properties, efficiency enhancement and economical feasibility of bioenergy projects. The biomass burning process is influenced by the fuel burn rate, the combustion reaction products, the adiabatic combustion temperature and the required air for complete combustion [6,7]. Therefore, a continuous development of biomass combustion systems is needed in order to fulfil the requirements in conversion efficiency, ease of operation and economical feasibility of biomass plants. This development must be based on increased knowledge about the complex phenomena involved in the biomass combustion process.

Modern biomass combustion plants and biomass boilers achieve an efficiency rate of over 90% and need sophisticated technology to control the process in order to minimize its environmental effects and promote efficiency [8]. However, the combustion control systems of modern biomass furnaces are not fully optimised yet and fulfil rather sub-optimally these requirements [9]. Another important objective for biomass plants optimisation is the reduction of unstable operation of combustion systems which is one of the reason for problems related to ash slagging and fouling as well as decreased lifetime of combustion equipment. Variability of biomass properties is large and causes variations in the process resulting in unstable operation of biomass combustion systems [10]. Modelling of biomass combustion can be used as a tool in order to deal with the multivariable interacting processes, multiple conflicting objectives and constrains which are the main problem related to combustion process control in biomass plants [11]. Modelling together with experiments can be used for parametric studies that reveal the relative influence of different combustion process variables on emission levels and combustion efficiency.

2. 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 represents a promising alternative for energy generation from biomass [12]. In large-scale biomass combustion appliances separation of different stages of thermal decomposition of the fuel on the grate as well as staged air combustion is applied, where 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 NOX emissions. The combustion chamber is divided into 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. The hot gases from the primary zone are oxidised in the secondary zone where the mixing of the combustible gases and secondary air should be as complete as possible. If good mixing is ascertained the emissions from incomplete combustion can be close to zero.

Thermal decomposition of biomass in a grate furnace consists of several interlinking processes of high complexity. 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 leave the fuel bed to the freeboard as 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 [14].

3. MATHEMATICAL MODEL FOR BIOMASS COMBUSTION

The combustion chamber of the furnace was divided into zones according to the individual steps of the biomass burning process. Illustration of the model concept is shown in Fig. 1. Each step of the biomass combustion will be analysed on the basis of energy balance equations, which have to be fulfilled at each moment of the combustion process. This approach enables a simplified description of the biomass combustion and solution of relevant equations in order to simulate the characteristics of biomass burning in a grate furnace. Generally speaking, in comparison to sophisticated models, simplified models are more useful from a practical point of view [15].

The purpose of the work is to develop a thermodynamical model for biomass combustion in a grate furnace which could be used for model based optimisation of control strategies. The mathematical model of biomass combustion 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 temperature profiles, gas composition and the combustion stoichiometry at each step of the combustion process and thus can be used for the evaluation of the influence of control parameters on the heat output of the system. Additionally mathematical modelling can be used to study how fuel properties such as moisture content and lower heating value influence the thermal decomposition of biomass in the fuel bed.

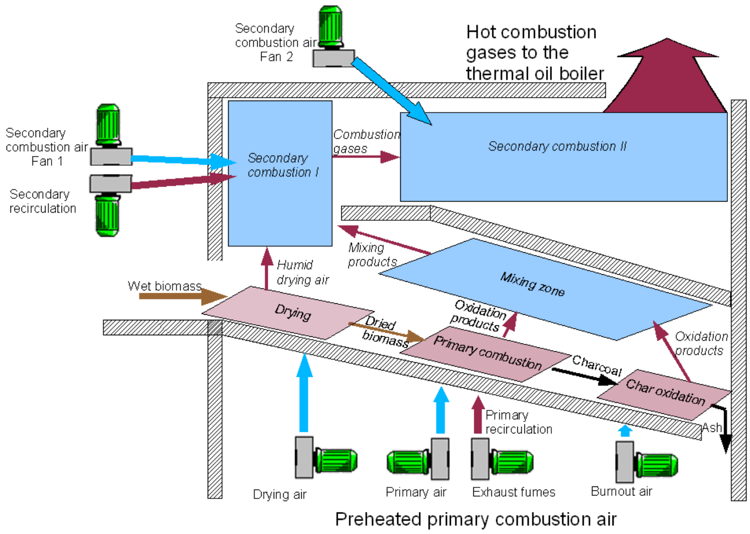

Fig. 1. Schematic view of biomass combustion in a grate furnace

3.1. DRYING ZONE

During drying the temperature remains around the boiling point due to the endothermic character of the process [16]. The rate of drying is related to the amount of heat provided by 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. The schematic illustration of drying zone as well as the energy and mass balance equations for the drying step is presented bellow.

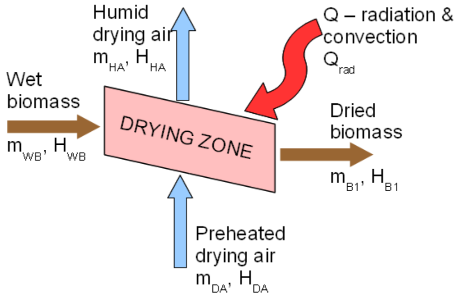

Fig. 2. Mass and energy balance for drying zone

Mass and energy balance equations:

$$\begin{cases} \dot{m}_{WB} + \dot{m}_{DA} - \dot{m}_{B1} - \dot{m}_{HA} = 0 \\ \dot{H}_{WB} + \dot{H}_{DA} - \dot{H}_{B1} - \dot{H}_{HA} + \dot{Q}_{rad} = 0 \end{cases} \tag{1}$$

3.2. PRIMARY COMBUSTION

During primary combustion the fuel is thermally decomposed which results in formation of volatiles with varying compounds. 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 volatile gases flowing out of particles prevent oxygen from diffusing to the surface of the particle, thus oxygen is consumed by the oxidation of the released gases [17]. The primary combustion stage comprises the thermal decomposition of the major portion of the fuel mass and gaseous compounds released during the 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.

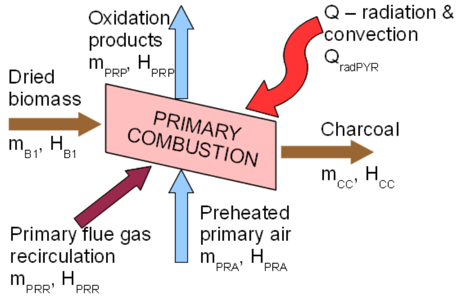

Fig. 3. Mass and energy balance for primary combustion zone

Mass and energy balance equations:

$$\begin{cases} \dot{m}_{B1} + \dot{m}_{PRR} + \dot{m}_{PRA} - \dot{m}_{CC} - \dot{m}_{PRP} = 0 \\ \dot{H}_{B1} + \dot{H}_{PRR} + \dot{H}_{PRA} - \dot{H}_{CC} - \dot{H}_{PRP} - \dot{Q}_{radPYR} = 0 \end{cases} \quad (2)$$

3.3. 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 [18]. The char oxidation takes place at much slower rate compared to the primary burning stage and comprises about 20% of the combustion time [19]. 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 CO2.

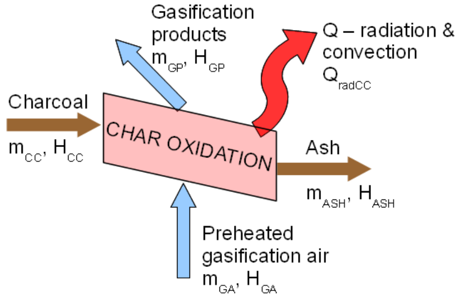

Fig. 4. Mass and energy balance for char combustion zone

Mass and energy balance equations:

$$\begin{cases} \dot{m}_{CC} + \dot{m}_{GA} - \dot{m}_{Ash} - \dot{m}_{GP} = 0 \\ \dot{H}_{CC} + \dot{H}_{GA} - \dot{H}_{Ash} - \dot{H}_{GP} - \dot{Q}_{radCC} = 0 \end{cases} \quad (3)$$

3.4. MIXING ZONE

Mixing of the gaseous products of charcoal oxidation and primary combustion is assumed before the gaseous mixture flows to the secondary combustion chamber. The schematic view of the mixing zone together with mass and energy balance equations for the reaction products is shown bellow.

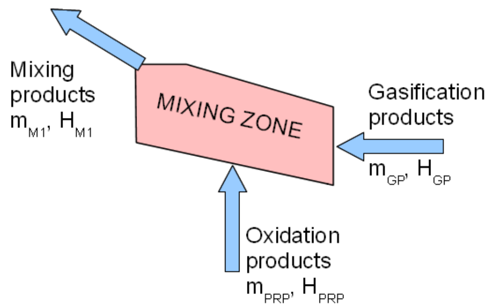

Fig. 5. Mass and energy balance for mixing zone

Mass and energy balance equations:

$$\begin{cases} \dot{m}_{GP} + \dot{m}_{PRP} - \dot{m}_{M1} = 0 \\ \dot{H}_{GP} + \dot{H}_{PRP} - \dot{H}_{M1} = 0 \end{cases} \quad (4)$$

3.5. SECONDARY COMBUSTION I

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. 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 [20].

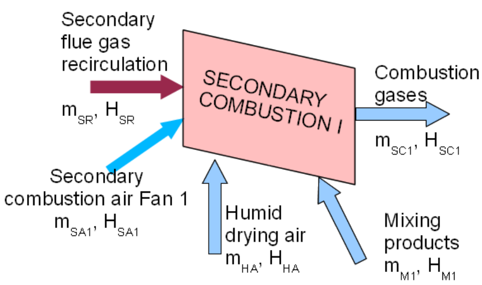

Fig. 6. Mass and energy balance for secondary combustion zone I

Mass and energy balance equations:

$$\begin{cases} \dot{m}_{M1} + \dot{m}_{HA} + \dot{m}_{SA1} + \dot{m}_{SR} - \dot{m}_{SC1} = 0 \\ \dot{H}_{M1} + \dot{H}_{HA} + \dot{H}_{SA1} + \dot{H}_{SR} - \dot{H}_{SC1} = 0 \end{cases} \quad (5)$$

3.6. SECONDARY COMBUSTION II

In order to provide optimised mixing conditions for gas combustion the secondary air supply was divided into two zones with separate combustion air fans.

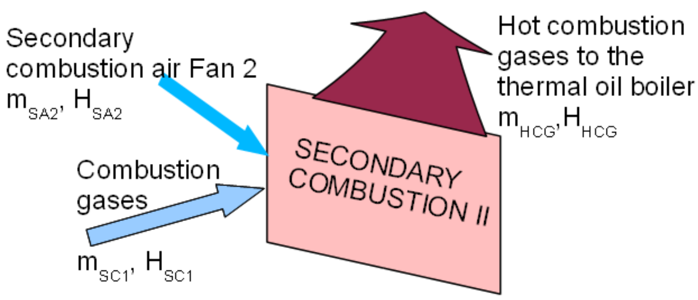

Fig. 7. Mass and energy balance for secondary combustion zone II

Mass and energy balance equations:

$$\begin{cases} \dot{m}_{SC1} + \dot{m}_{SA2} - \dot{m}_{HCG} = 0 \\ \dot{H}_{SC1} + \dot{H}_{SA2} - \dot{H}_{HCG} = 0 \end{cases} \quad (6)$$

4. CONCLUSIONS

Major motivation for applying simulation models for optimisation of biomass combustion is the need to improve their process operation. This is due to the growing demand for higher efficiency and the demand to improve the economical feasibility of energy generation based on biomass combustion. The presented mathematical model will be applied to analyse the operation of biomass combustion systems under real conditions. The described model will serve as a basis for analysis of the individual steps of the combustion process on the basis of energy balances, which have to be fulfilled in each moment of the process. The solution of the energy balance equations can be used to estimate the influence of control parameters and fuel properties on the performance of the biomass furnace.

The simulation results will be verified on the basis of measurement results from a grate furnace installed at biomass cogeneration plant near Stuttgart, Germany. The plant is equipped with a 6 MWth biomass furnace, which serves as thermal energy source for a cogeneration module. In order to enhance the efficiency of the system and to reduce temperature fluctuations in the combustion chamber following goals will be realised:

- analysis of the combustion process in order to define the main energy flows on the basis of energy balance equations
- parametric studies in order to achieve stable conditions of the thermal decomposition of biomass
- parametric studies in order to define optimal process parameter values (i.e. process requirements vs. material requirements

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SIMULATION DER BIOMASSEVERBRENNUNG IN ROSTFEUERUNGEN

ZUSAMMENFASSUNG: Biomasse zählt zu den wichtigsten erneuerbaren Energieträgern und mehr als 97% der Energie aus Biomasse wird in Verbrennungsanlagen erzeugt. In letzter Zeit erfolgte eine deutliche Weiterentwicklung der Verbrennungssysteme für Biomasse, die mit einen markanten Anstieg der Effizienz und Reduktion der Emissionswerte verbunden war. Der Betrieb und Wartung der Biomassefeuerungen erfordert jedoch nach wie vor ein gründliches Verständnis der Charakteristik der Biomasseverbrennung. Die Publikation beinhaltet die Beschreibung eines mathematischen Models für den Prozess der Biomasseverbrennung in einer Rostfeuerung, der auf Energiebilanzen für die einzelnen Etappen der thermischen Umsetzung von Biomasse basiert. Der auf diese Weise aufgebaute Model ermöglicht die Analyse der einzelnen Teilprozesse und eignet sich somit besonders für die Optimierung der Steuerungsstrategien von Biomasseverbrennungsanlagen.

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