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BIOMASS COMBUSTION MODEL FOR GRATE FURNACES

Abstract: Artykuł zawiera opis modelu procesu spalania biomasy w palenisku rusztowym. W przypadku palenisk rusztowych dużej mocy komora spania podzielona jest na strefy odpowidające poszczególnym etapom procesu spalania (suszenie, piroliza, zgazowanie węgla, dopalenie produktów gazowych). W celu przeprowadzenia analizy procesu termicznego rozkładu biomasy wyprowadzone zostały równania bilansu masy i energii dla poszczególnych etapów spalania. Uzyskany w ten sposób model może zostać wykorzystany do weryfikacji i poprawy strategii automatycznego sterowania kotłami biomasowymi dużej mocy.

1. INTRODUCTION

Biomass plays a key role in the global renewable energy supply and over 97% of energy generated from biomass is produced in biomass furnaces. There are still developing countries in which traditional biomass utilization delivers the main fraction on the generated energy. However, also in European countries biomass is the largest contributor (66%) among the renewable energy sources and there is a growing interest in optimization of energy generation systems based on biomass combustion.

Grate combustion of biomass is a typical applied technique for utilization of solid biomass potential as it combines reasonable investment and operational cost with relatively high efficiency. Combustion of biomass in a grate furnace is influenced by the fuel characteristics as well as by the operating conditions of the system such as primary air-flow rate, preheating of the combustion air and flue gas recirculation. The combustion chamber of modern biomass furnaces is separated into zones according to the individual steps of the thermal decomposition of biomass. The amount of combustion air fed to each zone can be controlled independently in order to ensure that each part of the combustion chamber is supplied with sufficient quantity of air. Flue gas recirculation is used for temperature control in the combustion chamber and to cool the grate. This allows achieving of more favorable temperature distribution, high ash burnout and low emissions of pollutants [1].

However, one of the problems by using solid biomass as a fuel are the varying fuel parameters like moisture content, lower heating value and geometric shape and size [2]. Furthermore stable combustion of biomass cannot always be achieved due to the fact that the commonly used control strategies are not fully optimized yet [3]. Due to the varying fuel parameters and changing working conditions of the furnace the temperature in the grate zone can vary between 700 and 900°C, which can negatively influence the combustion efficiency and increase the amount of emitted pollutants.

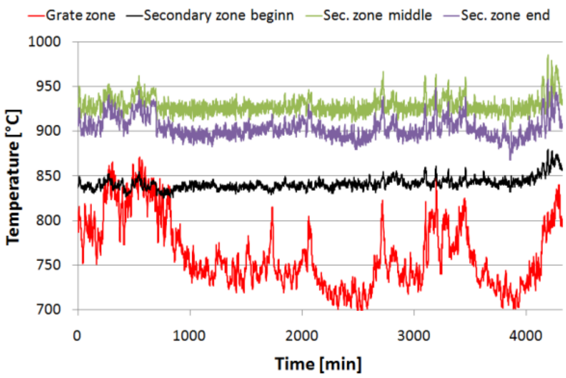

Fig. 1. Varying temperature values in the grate zone

An improved understanding of the influence of the operational parameters on the combustion behavior 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. To better understand the complex combustion process occurring in the grate boilers mathematical modeling can be used as a tool for analyzing the influence of fuel parameters and operational settings on the thermal decomposition of the fuel in a grate combustion system [4].

2. BIOMASS COMBUSTION PROCESS THEORY

The process of biomass combustion consists of a number of individual interlinking steps of high complexity. After the fuel enters the hot combustion chamber the moisture is driven out at temperature of 100°C by strong radiation from the furnace walls. When all moisture is released from the top layer the temperature starts to rise quickly to 260°C to the start point of the thermal decomposition of fuel, and the fuel bed on the grate is ignited. During thermal decomposition of fuel volatile compounds are driven out and released to the freeboard. As biomass consists in 85% of volatiles, the fuel mass loss rate achieves its maximum during devolatilisation. After the moisture and volatile matter have left the bed the final combustion stage of char burning begins.

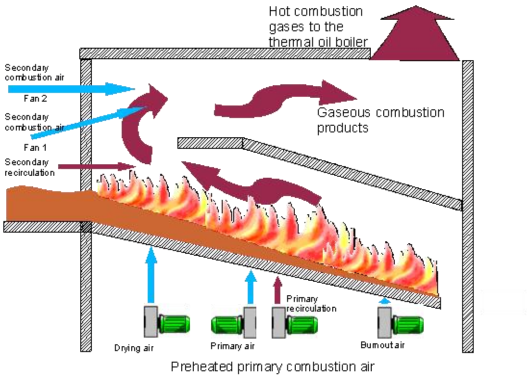

Fig. 1. Biomass furnace with primary and secondary combustion

In modern grate furnaces staged combustion is applied in order to reduce the NOx emissions and in order to achieve good part load behavior of the system. When air staging is applied the thermal decomposition of the fuel in the grate zone occurs in substoichiometric conditions (air/fuel ratio <1). The released gases are partly combusted in the over grate region resulting in a long flame above the grate. For substoichiometric 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, which 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.

3. MATHEMATICAL DESCRIPTION OF BIOMASS COMBUSTION

Based on the biomass combustion theory, a model for counter current combustion of biomass will be presented, in which each step of the process of thermal decomposition of biomass will be analyzed on the basis of energy balance equations. As the chemistry of thermal decomposition reactions is not known in detail, the description of the process has to be simplified for modeling purposes [5]. From a practical point of view, simplified models are more useful for model based control strategies then sophisticated models based on differential equations [6]. The purpose of this work is to develop a model for the thermal decomposition of wood chips on the grate, which will include moisture evaporation, primary burning stage and char combustion. This approach simplifies complex variations and makes the model suitable for model based control strategies. The temperature profiles in the combustion chamber, the fuel burning rate and the combustion gas composition are mainly determined by the thermal decomposition of biomass in the fuel bed. Therefore, a reliable bed model is a basis for a good model of biomass combustion in a grate furnace [7].

MOISTURE EVAPORATION

The energy for moisture evaporation is provided by the over-bed radiation and the moisture is driven out as evaporation proceeds. When the fuel enters the hot combustion chamber, whose temperature is about 850°C, the top layer of the fuel is exposed to radiation from the hot furnace walls. Radiation is assumed to be the major heat transfer mechanism between the fuel bed and the hot combustion chamber, and a proper calculation has to be applied in order to model the process [8]. A standard calculation routine for the radiative heat flux in the combustion chamber is presented in the following.

$$Q_{rad} = q_{rad} * A_p \tag{1}$$

$$q_{rad} = \left[\alpha_{str} * \left(T_{Fur} - T_{evap}\right)\right] \tag{2}$$

$$\alpha_{str} = \alpha_{conv} + \varepsilon_{DR} * \sigma_b * \left(\frac{T_{Fur}^4 - T_{evap}^4}{T_{Fur} - T_{evap}}\right) \tag{3}$$

[9]

where:

Q_{rad} – transmitted radiation [W]

q_{rad} – heat flux between furnace walls and fuel bed [W/m^2]

A_p – heat exchanging surface [m^2]

α_{str} – heat exchange coefficient [W/m^{2}K]

α_{conv} – convective heat transfer coefficient [W/m^{2}K]

T_{Fur} – furnace wall temperature [K]

T_{evap} – evaporation zone temperature [K]

ε_{DR} - radiation emissivity

σ_b – Stephan-Boltzmann constant, = 5.67 x 10^{-8} [W/m^{2}K^4]

PRIMARY BURNING STAGE

The primary burning stage starts after the top of the bed is ignited and results in formation of volatiles with varying compounds. During this stage the rest of fuel moisture is evaporated, volatile matter is released and part of the char is oxidized. The gaseous products released to the freeboard are oxidized with oxygen from primary air and these reactions are exothermic which results in higher gas temperature. The formulation of the model for primary burning stage is based on energy balance equation for incomplete oxidation of woody biomass.

$$CH_{1.4}O_{0.7} + v_1 H_2O_l + v_2 O_2 + v_3 N_2 \rightarrow v_4 CO_2 + v_5 CO + v_{CC} CC + v_7 H_2 + v_8 H_2O_l + v_9 O_2 + v_{10} N_2 \quad (4)$$

[10]

10 VARIABLES → 10 EQUATIONS:

- 4 equations – mass balance C, H, O, N
- 1 equation – charcoal oxidation
- 1 equation – air composition
- 1 equation from λ
- 1 equation from water content
- 2 equations from combustion stoichiometry

CHAR COMBUSTION

The final product of the primary combustion stage is charcoal, which consists in 90% of carbon and oxidizes in the final step of thermal decomposition of the fuel at temperatures of about 600°C. The primary products of char reaction with the oxygen in the primary air flow are CO and CO_2. Biomass consists in about 15% of fixed carbon and char burned in the final stage ranges from 20 to 85% of the total char burned. The char oxidation takes place at a much slower rate than the primary burning stage and comprises about 20% of the combustion time [11]. The heat released during charcoal oxidation has a large influence on the ignition rate of the bed and is related to the reaction products distribution (CO_2 and CO).

$$C(s) + \alpha O_2 \rightarrow 2(1-\alpha)CO + (2\alpha - 1)CO_2 \quad (5)$$

with the ratio of CO and CO_2 as:

$$\frac{CO}{CO_2} = 2500 \exp\left(-6420/T\right) \quad (6)$$

[12]

for temperatures between 730 and 1170 K

Ratios outside this temperature range are calculated using one of the limiting temperatures

4. APPLICATION TO PRACTICAL SYSTEMS

To meet the requirements in conversion efficiency and achieve economically feasible plant operation a continuous development of the conversion equipment is necessary. The presented model will be used to explain and understand the performance of biomass combustion applications under real conditions. It will provide help in understanding and explaining the performance of practical systems.

The above model will serve as a basis for the optimization of a biomass cogeneration plant located near Stuttgart, Germany. The plant is equipped with a 6 MW_{th} biomass furnace which serves as a thermal energy source for a cogeneration module. To optimize the efficiency and to reduce temperature fluctuations in the combustion chamber following goals will be realized:

- 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)

Park waste wood and wood scraps from landscaping residues are used as fuel for the researched combustion system. Natural wood scraps are relatively cheap fuel and their utilization as combustible is gaining more and more popularity. However, natural wood scraps are a kind of low quality fuel, heterogeneous in composition, containing a lot of moisture and non-combustibles. The presented model will be used to mathematically model the combustion of natural wood scraps. By doing so, the effects of the air supply rate, the fuel calorific value and moisture content will be analyzed. The analysis results will help designers as well as researches to predict the rough burning characteristics of natural wood scraps.

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