A study on the combustion dynamics of a biomass fuel bed in a BioGrate boiler

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ABSTRACT

The main objective of this research was to study fuel bed combustion dynamics of a BioGrate boiler with a mechanistic model. First, the fuel specific pyrolysis reaction rates were experimentally determined for the model. Second, the model was validated and finally, it was used to investigate the effects of the primary air flows on drying, pyrolysis and char consumption rates occurring inside the fuel bed. The research results are presented and the role of the dynamic behavior of the reactions on improving the efficiency of the biomass combustion process discussed.

1 INTRODUCTION

Biomass is receiving increasing attention as an alternative energy resource to fossil fuels due to increasing environmental concerns related to energy production. However, biomass is associated with varying fuel composition; in addition, it is highly dependent on storing conditions as well as on local and seasonal factors. Such variations affect power production efficiency and increased pollution. As a consequence a fuller understanding of the factors which affect the efficiency of power production is particularly important for the further development of these types of energy systems. Mathematical models have shown to be an excellent tool in assessing the complex physical phenomena of biomass combustion /2/.

Shin and Choi /13/ utilized modeling to determine the effect of process parameters on the combustion of municipal waste. The results indicated that a low air flow rate limits the combustion rate, whereas, an excessively high flow rate results in flame extinction. Van der Lans et al. /14/ described straw combustion with a two dimensional steady-state model and studied the effect of the combustion parameters on the burning of the fuel bed. Goh et al. /5/ have developed a model to simulate an incinerator bed; the results from the study indicated that fuel mixing can be modelled with swap probability method. The model developed by Yang et al. /15/ showed that air channelling can increase the concentrations of hydrocarbons in flue gas due to poor mixing. Similarly, a study by Kær /7/ suggested that poor mixing of flue gases and secondary air results in high CO concentrations and in unburnt carbon in fly ash. Miljkovic et al. /10/ constructed a model for straw bale combustion to obtain information such as a temperature profile of the fuel bed, a combustion rate and the produced chemical species. Hallett et al. /6/ found through experimental and modelling work that a volume-surface mean diameter can be used to describe non-uniformly sized particles. Combustion in a conical grate boiler was described mathematically by Boriouchkine et al. /2/ to provide information on the combustion

characteristics of woody biomass, with specific emphasis on the effects of moisture content, particle size and air flow on the combustion in a BioGrate boiler.

To summarize, these studies focused solely on combustion under steady-state conditions to evaluate the effect of several parameters, like the fuel moisture content and the air flow on the burning behavior of the biomass fuel bed. However, very little research has been done on the dynamics of the burning fuel bed which is a particularly important issue, as during the operation, a boiler is subject to several dynamic disturbances (Kortela and Jämsä-Jounela /8/), such as changes in a power demand. Consequently, the performance of a boiler is largely dependent on the behavior of a burning fuel bed under changing conditions.

Due to the importance of fuel bed combustion dynamics, this paper focuses on studying the local and furnace wide dynamic modelled of fuel combustion and, especially, the modelled of drying, pyrolysis and char combustion reactions as well as the temperature inside the bed. The analysis is done by inducing changes to the primary air flow of different magnitudes and amplitudes, and at different conversion stages to gain insight into the time-dependent combustion modelled . The simulations considered fuel combustion in a BioGrate boiler which is a conical grate boiler that operates under concurrent combustion conditions.

2 DYNAMIC MODEL OF A BIOGRATE BOILER

In a BioGrate boiler, biomass reacts through three main reaction pathways which can occur either in parallel or sequentially with respect to each other: drying, pyrolysis and char conversion and the mechanistic modelled of the BioGrate boiler considers these three stages of the biomass combustion. The burning fuel bed in a BioGrate boiler is modelled in one dimension using the walking grate assumption, since temperature gradients are more significant in a vertical than in a horizontal direction. Furthermore, since BioGrate boilers operate under concurrent combustion the combustion front propagates upward in the direction of the airflow.

2.1   Modelling of the solid phase mass conservation

The solid phase reactions considered by the model include drying, pyrolysis as well as char oxidation and gasification which in general can be described by Eq. (1).

$$\partial \rho_{s,j} / \partial t = -r_{s,j} \tag{1}$$

where $\rho_{s,j}$ is the mass concentration of each solid component (moisture, volatiles and char) while $r_{s,j}$ is the reaction rate of a respective component.

The rate of drying, Eq. (2), is defined by the energy available for evaporation. For numerical stability, the evaporation rate is multiplied by a conversion factor $\rho_{s,H2O}/\max(\rho_{s,H2O})$. Although this lowers the maximum local evaporation rates, as more energy is transferred to the consequent layers, the overall evaporation in the fuel bed rate remains the same as without the factor.

$$r_{s,H2O} = \max(0, (\rho_{s,H2O} / \max(\rho_{s,H2O}) C_p (T_s - 373.15K) / dt) / \Delta H_{vap}) \tag{2}$$

where T_s is the temperature of the solid phase and ΔH_{vap} is the vaporization enthalpy.

The pyrolysis reaction rate constants are given in Eq. (3) and (4).

$$k_{1,pyr} = 3.16 \cdot 10^2 \exp(-1.37 \cdot 10^5 / (RT_s)) \tag{3}$$

$$k_{2,pyr} = 2.21 \cdot 10^4 \exp(-7.84 \cdot 10^4 / (RT_s)) \tag{4}$$

Char is consumed in three different chemical reactions: oxidation, Eq. (5), (Branca and Di Blasi, /3/) with the associated CO/CO_2 ratio, Eq. (6), (Evans and Emmons, /4/) and reduction with H_2O, Eq. (7) (Senneca, /12/) and CO_2, Eq. (8) (Matsumoto et al. /9/).

$$k_{s,C} = 1.1 \cdot 10^6 \cdot \exp\left(-114.5 \cdot 10^3 / (RT_s)\right) \tag{5}$$

$$CO / CO_2 = 4.3 \exp(-3390 / T_s) \tag{6}$$

$$k_{s,H2O} = 9.99 \cdot 10^4 \cdot \exp\left(-136 \cdot 10^3 / (RT_s)\right)(1 - X)\sqrt{1 - 10\ln(1 - X)} \tag{7}$$

$$k_{s,CO2} = 1.1 \cdot 10^9 \exp\left(-260 \cdot 10^3 / (RT_s)\right)X \tag{8}$$

where X is the conversion stage of char.

For each heterogeneous char reaction, an effective reaction constant - given by Eq. (9) - is then calculated as follows:

$$k_{eff,i} = v_p k_{c,i} k_{r,i} / (v_p k_{c,i} + k_{r,i})$$ (9)

where v_p is the area to volume ratio of a particle, $k_{r,i}$ is the reaction constant and $k_{c,i}$ is the mass transfer coefficient.

2.2 Modelling of the gas phase mass conservation

The gas phase modelling, presented in Eq. (10), describes convection of each gaseous specie (O_2, N_2, CH_4, H_2, CO, CO_2, Tar, H_2O), combustion of CO (Eq. (11)) /1/, H_2 (Eq. (12)) /6/ and CH_4 (Eq. (13)) /6/, and gas formation in the pyrolysis reaction, $Y_{g,i} r_{s,pyr}$.

$$\partial(\rho_{g,i} \varepsilon_b)/\partial t - \partial(v_g \rho_{g,i} \varepsilon_b)/\partial x = -r_{g,i} + Y_{g,i} r_{s,pyr}$$ (10)

where $\rho_{g,i}$ is the mass concentration of a gaseous specie, ε_b is the bed porosity, v_g is the velocity of the gas, $r_{s,pyr}$ is the pyrolysis reaction rate, while $Y_{g,i}$ is the mass fraction of the forming gaseous pyrolysis product.

$$r_{g,CO} = 1.3 \cdot 10^{14} \exp(-125.5 \cdot 10^3 /(RT_g)) C_{CO} C_{O2}^{0.5} C_{H2O}^{0.5}$$ (11)

$$r_{g,H2} = 2.14 \cdot 10^{14} \exp(-129/(RT_g)) C_{O2}$$ (12)

$$r_{g,CH4} = 5.6 \cdot 10^{12} \exp(-103.8/(RT_g)) C_{O2}$$ (13)

2.3 Modelling of the solid phase energy conservation

The energy equation for the solid phase describes heat conduction, heat exchange between the phases, energy consumed in the drying and pyrolysis reactions and energy gained in char combustion (Eq. (14)):

$$C_s \rho_s \partial T_s / \partial t = \partial(k_{s,eff} \partial T_s / \partial x)/\partial x + k_{conv} v_p (T_g - T_s) + \sum Q_{reactions,solid} + k_a (I^+ + I^-) - k_a \sigma T_s^4$$ (14)

where k_{conv} is the convective heat transfer coefficient, $k_{s,eff}$ is the effective heat conduction coefficient of the solid phase, k_a is the absorption coefficient, I^+ is the radiative flux in the direction of the fuel layer surface, I^- is the flux in the direction of the grate, T_g is the gas phase temperature, T_s is the solid temperature and $Q_{reactions,solid}$ is the energy produced or consumed in the solid phase reactions (drying, pyrolysis and char reactions), σ is Stefan-Boltzmann constant.

The radiative heat transfer inside the bed is described with a two-flux model given by Eq. (15) and (16), where the absorption and scattering coefficients are given by Eq. (17) where d_p is the fuel particle diameter.

$$dI^+/dx = -(k_a + k_s) I^+ + k_s I^- + 1/2 k_a \sigma T_s^4$$ (15)

$$-dI^-/dx = -(k_a + k_s) I^- + k_s I^+ + 1/2 k_a \sigma T_s^4$$ (16)

$$k_a = -1/d_p \ln(\varepsilon_b), \quad k_s = 0$$ (17)

2.4 Modelling of the gas phase conservation

The energy continuity equation, Eq. (18) of the gas phase considers the heat exchange between the gas and solid phases, the energy received through gas convection, and the energy gained from carbon monoxide, methane and hydrogen oxidation.

$$\rho_g \, \partial(H_g \varepsilon)/\partial t + \partial\big(\varepsilon v_g H_g\big)/\partial x = \sum Q_{reactions,gas} - k_{conv} v_p (T_g - T_s) \tag{18}$$

where H_g is the overall enthalpy of the gas phase and $Q_{reactions,\,gas}$ is the energy released in the oxidation of CO, CH_4 and H_2.

3. COMBUSTION DYNAMICS OF A FUEL BED

3.1 Local combustion dynamics

Combustion of a biomass fuel bed provides energy for boiler operation and thus boiler dynamics depend to a large extent on the fuel combustion dynamics. In this study, the combustion dynamics were analysed with the mechanistic model by changing the rate of primary air flow fed into the burning fuel bed and by analyzing the effects on drying, pyrolysis and char combustion. In simulations, the bed density was 150 kg/m3 on a dry basis, moisture content 55 w%, the fuel layer was 0.5 m high, the freeboard temperature 900 °C and the fuel speed 1.5 mm/s. The air flows were varied between 3 m3/s and 5 m3/s which is the nominal air flow range used in BioGrate boilers.

The dynamic responses shown in Figures 1 and 2 indicate a significant effect of the air flow on the amount of the released gas and especially on the amount of released water. The effect of the air flow on the drying rate is also confirmed by the reaction rates presented in Figures 3 and 4 which show that the increase in the air flow notably increases the drying rate. Furthermore, the results suggest that water evaporation is only affected by the current air flow rate and not by the previously used flows as the simulations with two different air flows indicate that evaporation rate dependent only on the air flow rate, but not on the pattern of changes in the flow. The dependence of drying on the air flow was particularly well demonstrated by the simulation with a gradually increasing air feed which showed that the combustion time was significantly shortened compared to the other cases. Such behavior indicates that the increase in the gas flow also improves the overall heat exchange due to increased convection which, in turn, enhances drying. Similar to drying, the pyrolysis reaction rates also showed the dependence on the air flow, however, the influence was slightly smaller. For instance, the decrease in the air flow from 5 to 3 m3/s, which occurred between 0.5 and 1 m from the grate center (Figure 3), decreased the drying rate by 40% whereas the pyrolysis of the first component was decreased by 30 %.

3.2 Furnace wide combustion dynamics

Furnace wide combustion dynamics were investigated by switching fuel moisture content at time instance t = 0 s from 55 w% to 20 w%. Due to the higher heating value of the drier fuel and in order to maintain the constant power output, the control system gradually decreases the fuel feed rate and air supply. This control action was reproduced in the simulations by decreasing the fuel speed in proportion to the air supply (Figure 6).

The results demonstrated (Figure 6) that the release rate of each combustion product (H2O, CO, CO2, CH4 and Tar) had a unique behavior. Similar to the local combustion dynamics the water evaporation had the most dependence on the air supply rate. Furthermore, the release rate of water vapor reached the new steady state quicker compared to the other components. In addition, the decrease in air flow velocity below 0.025 m/s did not decrease the evaporation rate further as was observed in the release of other components. In case of the carbon dioxide, its release rate stabilized, although not completely, before that of carbon monoxide. In addition, the amount of produced carbon monoxide was less affected by the change in the air supply than the amount of carbon dioxide. This suggests that oxygen is mostly consumed in char oxidation reaction to form CO and that at the combustion temperature of the drier fuel, carbon monoxide is the main product of char combustion. In general, only the carbon dioxide formation reached its new steady state with the air flow while other gases, except H2O, reached it only after 300 s.
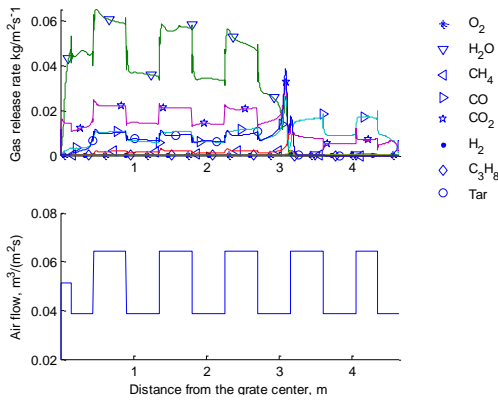
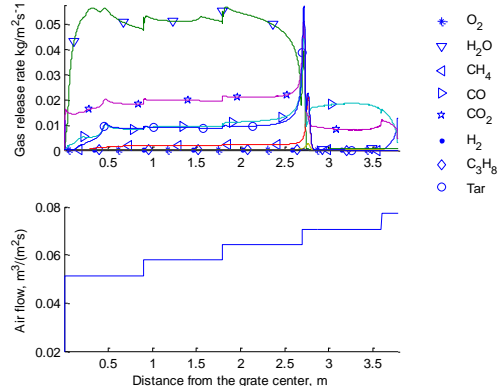**Figure 1.** Gas phase composition during the simulation with steps in the airflow

Figure 2. Gas phase composition during the simulation with a gradual increase in the airflow
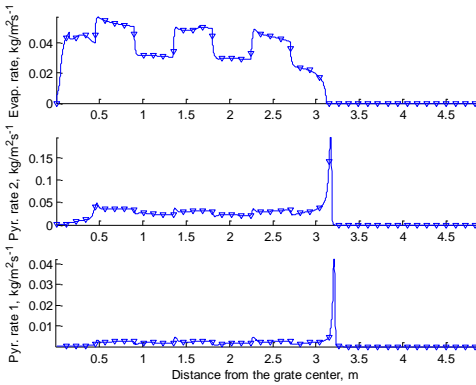

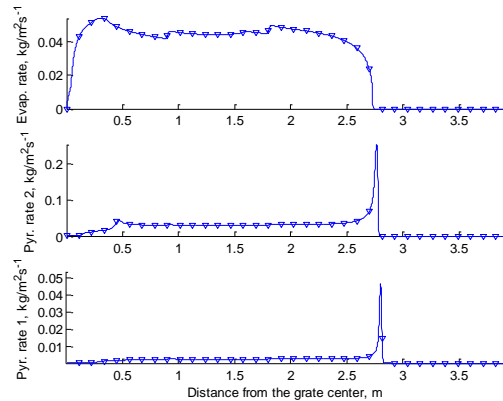**Figure 3.** Reaction dynamics during the simulation with steps in the airflow

Figure 4. Reaction dynamics during the simulation with a gradual increase in the airflow
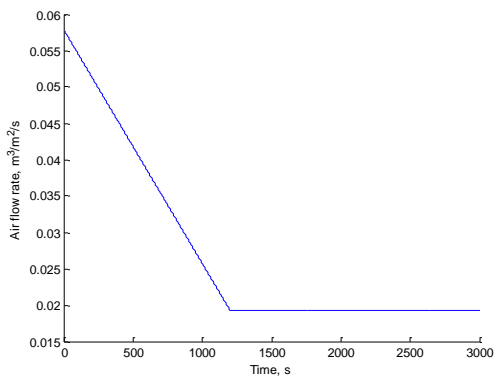

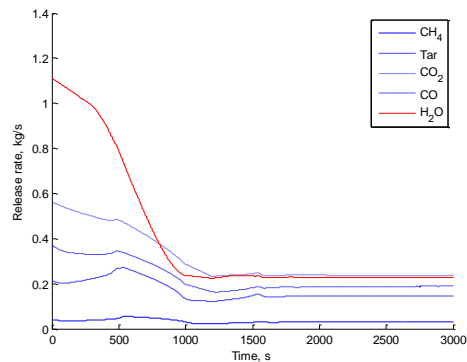**Figure 5.** Air flow rate used for simulations

Figure 6. Gas release rate from the furnace

5 CONCLUSIONS

Simulations showed that combustion dynamics are largely dependent on the air flow. All reactions demonstrated a quick local response to the changed conditions. In the furnace wide investigation, the major changes in gas formation occurred quite rapidly, although the final settling time for the release rates of some components was several minutes. This implies that boilers which operate under concurrent combustion conditions can relatively

quickly respond to changes in the power production demand. Furthermore, the dynamics of the system results in a quick response to the fuel bed combustion on the control actions.

Based on the simulated behavior of drying, pyrolysis and char reactions, it can be argued that moisture evaporation controls the pyrolysis rate by absorbing most of the energy produced by char combustion thus preventing the temperature from reaching the point where pyrolysis could start. Furthermore, the increased air flow influences the pyrolysis rate less significantly since drying consumes most of the extra energy generated by char oxidation. However, the results indicated that drying rate can be effectively controlled by the air flow and thus the combustion of fuels with high moisture content, which are extensively used in BioGrate boilers, can be intensified by using higher air flow rates.

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