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CFD ANALYSIS OF AIR STAGING AND FLUE GAS RECIRCULATION IN BIOMASS GRATE FURNACES

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ABSTRACT
Computational Fluid Dynamics (CFD) is increasingly being used for the optimisation of industrial furnaces. Due to the high complexity of thermal decomposition and combustion processes in biomass fuel beds, only few research work has been performed so far in order to introduce CFD as a cost-efficient tool in the optimisation of biomass grate furnaces. In the present case study the influence of air staging and flue gas recirculation on the flue gas burnout as well as on mixing conditions and temperature distribution was investigated. Simulation results for a Low-NO_x biomass furnace with two different grate systems – travelling grate and horizontally moving grate - are presented. The CFD calculations reveal a considerable potential to optimise the mixing of unburned flue gas with air by appropriate air staging and flue gas recirculation. Additionally, the temperature distribution and control in the combustion chambers can be improved in order to prevent slagging, fouling and material stress. The results of the numerical investigations can be taken as guidelines for an improved design and process control of biomass grate furnaces.

1 INTRODUCTION

In countries like Austria with large biomass resources, the combustion of wood fuels provides an important possibility of reducing emissions of the greenhouse gas CO_2. A techno-economic optimisation of the combustion system is necessary in order to successfully establish renewable energies in the market of heat and power generation. Due to the increasing performance of computers, Computational Fluid Dynamics (CFD) is gaining importance as a cost-efficient tool for the design and optimisation of industrial furnaces and boilers. But as thermal decomposition and combustion processes in solid biomass fuel beds are of high complexity, only few research work ([2], [3]) has been performed so far concerning modelling and optimisation of biomass grate furnaces with CFD. In the present work, the influence of air staging and flue gas recirculation on the combustion process of a recently developed Low-NO_x grate furnace with a nominal boiler capacity of 550 kW_{th} was analysed by means of CFD calculations. The commercial CFD code FLUENT 5^{TM} was used for the CFD modelling of turbulent reacting flow including radiative heat transfer. The mass and energy fluxes from the biomass fuel bed (drying, devolatilisation and heterogeneous char coal combustion) into gas phase, which form the boundary conditions for subsequent CFD calculations, were calculated with a simple empirically derived model.

2 DESCRIPTION OF THE BIOMASS FURNACE

Figure 1 shows a schematic diagram of the geometry of the grate furnace modelled. The combustion chambers are arranged vertically in order to save investment costs by minimising the necessary chamotte ducts. The geometry of the combustion chamber including the secondary air nozzles has been optimised in a previous work ([3]). The furnace is designed for Low-NO_x operation, and is therefore divided into two combustion zones. The primary combustion zone is designed as an air lean hot reduction zone with sufficient residence time for the flue gas (0.6 – 0.8 s at nominal power) to reduce NO_x emissions by primary measures. The secondary combustion zone is designed as an air rich burnout zone. Flue gas recirculation is used for temperature control, allowing selective recirculation into the secondary combustion zone and/or into the primary combustion section below the grate. Furthermore, the combustion chamber can be combined with two different grate systems depending on the biomass fuel used - a travelling grate for homogeneous and dry biomass fuels (especially waste wood and pellets) and a horizontally moving grate for a broader biomass fuel assortment, especially suitable for heterogeneous and wet biomass fuels (e.g. bark).

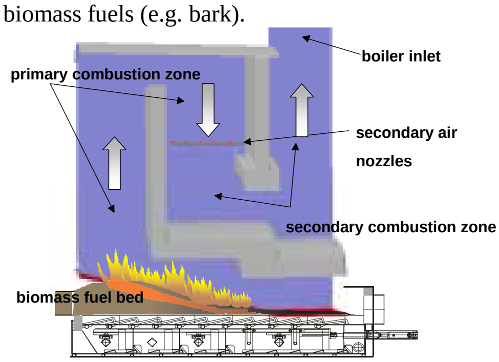

Figure 1: Combustion chambers of the biomass grate furnace modelled equipped with a horizontally moving grate

3 MODELLING

3.1 Modelling of the biomass fuel bed – CFD boundary conditions

An empirically derived model was used for the calculation of the mass and energy fluxes from the fuel bed to the gas phase which are used as boundary conditions for subsequent CFD calculations. Experiments have shown a linear correlation between the individual

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components H_2O, C, H, N and O released from the biomass fuel bed. This allows the mathematical description of the fuel consumption with one leading parameter (e.g. release of C), for which a profile has to be described. This description is based on test runs performed for different fuel types at a pilot-scale grate furnace by repeatedly taking and analysing samples from different parts of the fuel bed. Furthermore, conversion parameters are defined in order to calculate the local concentrations of different species (C_mH_n, CO, CO_2, H_2, H_2O, O_2) in the flue gas released from the fuel bed along the grate. These conversion parameters are based on assumptions and literature ([5]). In order to achieve a more detailed description of heterogeneous biomass combustion on the grate, the model is being developed further. The modelling parameters needed (profiles for the consumption of the solid biomass fuel components and conversion parameters) are determined by measurements at a specially designed lab-scale reactor with a hot gas FT-IR measurement system, which allows several flue gas components in the hot furnace (CH_4, CO, CO_2, H_2O) to be determined in-situ. At the current state of development, only a forward-coupling of heterogeneous biomass combustion on the grate and turbulent reacting flow of flue gas in the combustion chamber is assumed, while the radiative heat transfer between the fuel bed and the surrounding combustion chamber and the flue gas is not considered explicitly. However, the model was developed focusing on biomass grate furnaces with furnace geometries similar to the one shown in Figure 1 and is reasonably accurate regarding its application for CFD calculations aiming at the optimisation of flue gas burnout, the minimisation of furnace volume and the prevention of slagging, fouling and material stress. Figure 2 shows different profiles of local temperature and concentration of H_2O in the flue gas released from the fuel bed along the grate, calculated with the empirically derived model explained above.

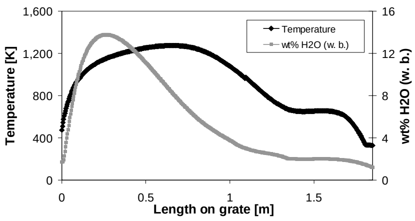

Figure 2: Profile of flue gas temperature and water concentration [wt% (w. b.)] of the flue gas released from the fuel bed along the grate

Explanations: *Primary air ratio = 0.8, flue gas recirculation ratio = 0.3, recirculation under the grate, fuel type: waste wood (water content: 16 wt% (w.b))*

3.2 CFD Modelling

The commercial CFD-solver FLUENT 5™ for unstructured grids, which allows the modelling of complex geometries and solution-adaptive grid refinement, was applied. The SIMPLE algorithm was used for pressure-velocity coupling and a second-order Upwind Scheme for the discretisation of convective terms of the transport equations. The Realizable k-ε Model used for turbulence modelling is nearly as numerically robust and CPU efficient as the Standard k-ε Model but provides substantial improvements for flows including rotation, strong streamline curvature and recirculation zones (theory see [4]). The Discrete Ordinates Model (DOM) solving the radiative transport equation for a finite number of discrete solid angles was used for radiation modelling where the accuracy of the model and the CPU time needed increase with an increasing angular discretisation. A 3-step reaction mechanism proposed by Brink et. al ([1]) considering the species C_mH_n (represented by methane), H_2, CO, CO_2, H_2O, CO_2 and O_2 was used for combustion modelling.

$$C_mH_n + \left(\frac{m}{2} + \alpha\frac{n}{4}\right)O_2 \xrightarrow{r_1} mCO + \left((1-\alpha)\frac{n}{2}\right)H_2 + \alpha\frac{n}{2}H_2O$$

Equation 1

$$CO + \frac{1}{2}O_2 \xrightarrow{r_2} CO_2$$

Equation 2

$$H_2 + \frac{1}{2}O_2 \xrightarrow{r_3} H_2O$$

Equation 3

The symbol α (= Mole H_2O formed / (Mole H_2 + Mole H_2O formed)) in Equation 1 describes the relation between the amounts of H_2 and H_2O formed and calculated under the assumption of partial equilibrium with the species CO and CO_2 (water-shift reaction). For the modelling of turbulent combustion, the global reaction mechanism was implemented in a Finite Rate Chemistry / Eddy Dissipation Model (EDM), which is implemented in most commercial CFD codes. The reactions in Equation 1 and 3 are assumed to be controlled by turbulent mixing. The reaction rate described in Equation 2 (consumption of CO) is determined by the lower (limiting) value of the kinetic rate or the turbulent mixing rate. All reactions are assumed to be irreversible. For a more detailed description of the models implemented in FLUENT 5 see ([4]).

4 DISCUSSION OF SIMULATION RESULTS

In order to obtain more detailed information about the operating behaviour of the biomass grate furnace modelled and to derive guidelines for improved design and operation, an analysis of different air staging and flue gas recirculation ratios and methodologies was performed. Various influencing parameters were investigated for that purpose. Table 1 sums up the basic operating data and constraints used for the CFD analysis.

Table 1: Operating data used for the CFD analysis (reference case)

parameter	value	unit
boiler load	550	kW_{th}
primary air ratio	0.8	
total air ratio	1.6	
recirculation ratio	0.3 (recirculation under the grate)	
fuel type	waste wood	
water content	16	wt% (w.b.)

The CO emissions at the boiler inlet calculated for the reference case are far below the emission limits. CO values and CO distribution in the furnace should be regarded only as trends. Furthermore, the temperature peaks are located at the transition between the first and second vertical combustion chamber and amount to about 1,330°C (Figure 4). NO_x formation and reduction were not considered in the CFD analysis for two reasons: No

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reliable model describing the release of nitrogen compounds from fixed biomass fuel beds into gas phase was available (model development and implementation is ongoing), nor does FLUENT 5™ provide a model describing gas phase NO_x chemistry in turbulent flows taking into account relevant reactions for biomass combustion (will be implemented by user defined functions in the near future). However, the furnace geometry used has been developed with regard to NO_x reduction by primary measures, i.e. by appropriate air staging and by assuring a mean residence time of the flue gas in the air lean primary combustion zone of 0.6 - 0.8 sec. at nominal load.

4.1 Arrangement of nozzles for injection of secondary air and flue gas

The design and arrangement of nozzles for secondary air and flue gas injection is the key to an optimised air staging and flue gas recirculation technique. In the present case the nozzle geometry was optimised by variation of the nozzle design and can also be applied to furnaces with similar geometries and flow conditions. Figure 3 shows the profiles of CO concentration as an indicator for flue gas burnout for the optimised nozzle design.

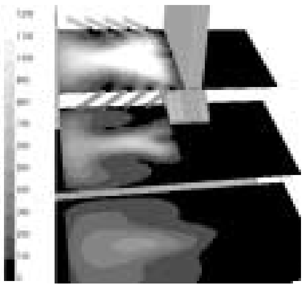

Figure 3: CO distribution [vol-ppm] in different cross-sections near secondary air injection
Explanations: *Primary air ratio = 1.0, total air ratio = 1.6, flue gas recirculation ratio = 0.3, recirculation under the grate, fuel type: waste wood (water content: 16 wt% (w.b))*

The optimised nozzle design aims at a highly turbulent mixing of secondary air (and/or recirculated flue gas) with the combustible gases by a high stagnation momentum and the stimulation of a swirling flow. This can be implemented by an appropriate arrangement and design of the nozzles in order to homogenise the flow, the composition of the flue gas and the temperature distribution over the cross-section of the combustion chamber. The nozzle geometry shown in Figure 3 was chosen for the furnace geometry investigated.

4.2 Variation of the primary air ratio

The primary air ratio possibly varies depending on the grate system and biomass fuel used. In order to study the influence of the primary air ratio on the overall combustion process it was varied between the values 0.8 (horizontally moving grate) and 1.0 (travelling grate) keeping the total combustion air ratio constant (1.6). Figure 4 and Figure 5 show the calculated temperature profiles. It can be seen that a decreasing primary air ratio (within the considered range) leads to higher temperature peaks at the transition between the first and second vertical combustion chamber due to a higher concentration of unburned flue gas compounds released from the biomass fuel bed. This should be regarded concerning slagging and material stress. The primary air ratio should not be too low without additional measures, because this would lead to higher concentrations of combustible flue gases released from the fuel bed, resulting in higher furnace temperature and CO concentrations despite the higher stagnation momentum of the secondary air jets (if the total excess air ratio is kept constant).

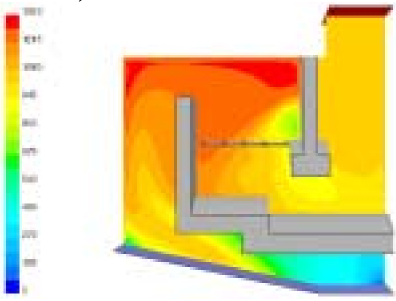

Figure 4: Temperature profile [°C] in the symmetry plane of the furnace for a primary air ratio of 0.8
Explanations: *Operation data: Reference case Calculation data: Temperature peak = 1330 °C, CO emissions at the furnace outlet = 18.0 mg/Nm^3 (dry flue gas, 13 vol% O_2)*

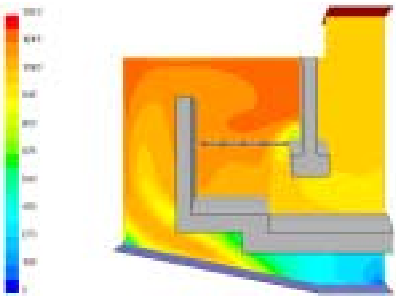

Figure 5: Temperature profile [°C] in the symmetry plane of the furnace for a primary air ratio of 1.0
Explanations: *Operation data: Reference case except varied parameter primary air ratio = 1.0) Calculation data: Temperature peak = 1275 °C, CO emissions at the furnace outlet = 12 mg/Nm^3 (dry flue gas, 13 vol% O_2)*

Furthermore, the changed oxygen content in the primary combustion zone results in a change in the thermal decomposition process in the fuel bed. Due to uncertainties in the model used for simulating the fuel bed, possible variations regarding the release of flue gas components into gas phase should be checked. Furthermore, a varying primary air ratio leads to a change in the amount of secondary air and, consequently, also in the local mass, momentum and energy fluxes in the different combustion sections, which results in different profiles of velocity, temperature and species concentration.

Therefore, it can be stated that an overall optimisation of biomass grate furnaces should fulfil two requirements. On the one hand, the sensitivity of CFD modelling results to possible changes in the thermal decomposition behaviour of the fuel bed must be checked and evaluated. On the other hand, simulations should be performed for each operating condition possibly changing the flow conditions in the different combustion sections.

4.3 Variation of the total flue gas recirculation ratio

The recirculation ratio was varied from 0.30 (adiabatic furnace temperature = 1,050 °C) to 0.39 (adiabatic furnace temperature = 950 °C) in order to investigate the influence on flue gas burnout and temperature distribution (flue gas recirculated below the fuel bed). The simulation results showed that increased flue gas recirculation leads to a significant decrease of CO concentrations calculated at furnace outlet (about 40% in comparison to the reference case) and to lower temperature peaks, and can therefore be recommended to improve the mixing conditions of combustible gases and air. Furthermore, a higher flue gas recirculation ratio also provides improved temperature control. Nevertheless, it has to be considered that a higher degree of flue gas recirculation also leads to a higher power demand of the flue gas fans and to a higher volume flow in the boiler section, increasing operating costs. Therefore, both technological and economic aspects must be taken into account in overall system optimisation.

4.4 Selective injection of recirculated flue gas

Based on the findings of the previous chapters, parallel flue gas recirculation trough the secondary air nozzles and below the grate was investigated keeping the total amount of recirculated flue gas constant. The results showed that both the CO emissions calculated at furnace outlet and the local temperature peaks showed a minimum for a certain stream ratio depending on the primary air ratio and on the amount of excess air chosen. Since CO emissions were low for all calculations performed, the lowering of temperature peaks in the furnace was taken as a determining parameter for the optimal stream ratio (recirculation primary combustion zone / recirculation secondary air nozzles = 3/1). In general, a selective injection of recirculated flue gas, depending on the furnace geometry and the operating conditions, can be recommended for optimised flue gas burnout and improved temperature control in the furnace in order to impede slagging, fouling and material stress.

4.5 Variation of the amount of excess air

Based on the results of the CFD calculations, the CO concentrations calculated at furnace outlet were far below the emission limits of 100 mg/Nm^3 (dry flue gas, 13 vol% O_2). This indicates the possibility of reducing excess air in order to increase the thermal efficiency of the boiler and to reduce the power demand of the secondary air fans. Consequently, a reduction of the total combustion air ratio from 1.6 to 1.2 was investigated by CFD simulations. The results showed that the calculated CO concentrations remained below the emission limit even in the case of the lower total combustion air ratio. The results should be regarded only as trends but indicate that the amount of excess air can be reduced considerably by an optimisation of furnace geometry, air staging and flue gas recirculation.

5 SUMMARY AND CONCLUSIONS

A CFD analysis of air staging and flue gas recirculation was performed for a newly developed Low-NO_x biomass grate furnace. Flue gas burnout, furnace temperature distribution as well as combustion efficiency were improved by CFD based optimisation of air staging and injection of recirculated flue gas. A first prototype was built on the basis of the simulation results of the present and a previous study. Currently, the simulation results are being checked and evaluated through comparisons with measurements. The following guidelines were derived for an improved design of biomass grate furnaces:

- The proper design and arrangement of the nozzles for the injection of secondary air and flue gas makes a homogenisation of the flue gas flow possible in order to achieve an improved flue gas burnout, a destruction of CO strains as well as lower temperature peaks in the furnace.
- For an overall optimisation of biomass grate furnaces, simulations should be performed for each operating condition changing the flow conditions in the different combustion sections. Furthermore, the sensitivity of CFD modelling results to possible changes in the thermal decomposition behaviour of the fuel bed has to be checked and evaluated.
- A higher flue gas recirculation ratio leads to an increased rate of flue gas burnout and a more homogeneous furnace temperature distribution due to improved mixing conditions. In order to define the optimum flue gas recirculation ratio, a CFD based sensitivity analysis is recommended, taking into account technological and economic aspects.
- Selective flue gas recirculation makes an additional reduction of CO emissions and local temperature peaks possible.
- The amount of excess air necessary to keep CO emission limits can be reduced by optimised air staging and flue gas recirculation. This is of special importance regarding the improved design of grate furnaces due to the achievable increase in efficiency.

6 LITERATURE

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