INFLUENCE OF UNEVEN FUEL DISTRIBUTION ON A GRATE ON GAS FLOW AND COMBUSTION QUALITY

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ABSTRACT: Grate boilers are widely applied for biomass combustion and achieve high combustion quality in good operation conditions. However, uneven fuel distribution such as e.g. uncovered grate sections can occur due to part load operation or changing fuel properties. Uncovered grate sections influence the flow conditions and are assumed to cause increased emissions from incomplete combustion such as carbon monoxide (CO). The objective of this investigation is to analyse the influence of the grate coverage on the flue gas emissions by experiments and CFD modelling. Experiments are performed on a 1.2 MW moving grate boiler. The grate coverage is varied by different primary air settings. To identify the grate coverage and to derive gas profiles for the CFD calculations, pyrolysis gas measurements (CO, CO_2, CH_4, H_2, O_2 and H_2O) above the grate with an oil cooled sampling probe are performed. Flue gas analysis is performed with use of CO as indicator for the combustion quality. Experiments and CFD modelling confirm a relevant influence of the grate coverage on the combustion quality. With increasing uncovered area at the end of the grate, CO emissions increase. A change from an ideally covered grate with 80% coverage and CO emissions of 25 mg/m^3 at 11 vol.-% O_2 to a highly uncovered grate with 40% coverage, a CO increase by a factor of 2.5 is found in experiments. CFD modelling predicts an increase by a factor of 3.9. Hence modelling is qualitatively validated by experiments and uneven fuel distribution is confirmed as a source of increased emissions. Measures to reduce emissions due to uncovered grates are discussed.

Keywords: Grate combustion, emissions, modelling, measurement, sampling, wood chips.

1 INTRODUCTION

Grate combustion is widely applied for biomass fuels with high ash and moisture content in typical applications from 0.5 – 25 MW [1,2]. High combustion quality for flue gas and grate ash is usually achieved at full load operation. However, part load operation or changing fuel properties (e.g. lower moisture content), can lead to uneven fuel distribution on the grate e.g. with uncovered grate sections in the second part of the grate. Under typical operation conditions, a nearly constant air flow through the grate leads to leaking primary air (LPA) in uncovered sections. This can result in uncontrolled flow conditions in the freeboard above the grate and in streaks with increased excess air and reduced temperatures.

Due to these negative effects on the flow conditions, an uneven fuel distribution is assumed to cause a reduction of the combustion quality thus resulting in increased pollutants such as carbon monoxide (CO) and other products of incomplete combustion in the flue gas.

The aim of the present work is to investigate the influence of an uneven fuel distribution on a moving grate on the fluid flow of combustible gases and air, the temperature profiles, and the combustion quality to derive measures to improve the combustion chamber geometry and the control concept for the fuel transport on the grate.

For this purpose, the combustion conditions for different situations of fuel and primary air distribution on the grate are compared by two methods:

a) based on calculations by Computational Fluid Dynamics (CFD), and

b) by measurements of gas concentrations and temperature profiles above the grate and monitoring of the flue gas quality in a 1.2 MW grate boiler under different operation conditions, i.e., with varying levels of the grate coverage (GC).

2 EXPERIMENTAL METHOD

2.1 Grate boiler

The experiments are carried out on a 1.2 MW forward acting grate boiler. The grate has a length of 2.1 m consisting of 7 grate bars and a width of 1.1 m.

Primary air is supplied through two grate zones, a first section with 4 grate bars and a second section with 3 grate bars. Secondary air is fed over the fuel bed from the side walls as well as from the rear wall. Additional combustion air is supplied in the post combustion chamber as shown in Fig. 1.

2.2 Operating Conditions

The boiler is operated at near full load (90%) with wood chips with a moisture content of 34% - 42% on wet basis. Due to changing moisture content of the fuel, the total amount of combustion air is varied in order to maintain a constant heat output for different test runs. The average excess air ratio (λ) varies in the range of 1.7 to 2.1 for the different test runs.

During the tests, the excess air is oscillating induced by the control of the fuel feed at constant air supply. The amplitude of this oscillation is approximately 1.5 vol.-% O_2 and causes a respective oscillation of CO emissions in the flue gas. Furthermore, the periodic movement of the grate bar induces an additional oscillating behaviour of the gas concentrations in the flue gas and in the pyrolysis gases.

2.3 Gas sampling and analysis over the grate

The gas sampling is performed with an oil cooled steel probe (Fig. 1). The mass flow of the oil is controlled to adjust a constant gas temperature of 180°C. The oil is cooled by an external heat exchanger (Fig. 2). With this procedure, the pyrolysis gases are immediately quenched to avoid further reactions inside the sampling probe. On the other hand, the temperature level is high enough to safely avoid condensation of water vapour and also to avoid significant tar condensation in the probe.

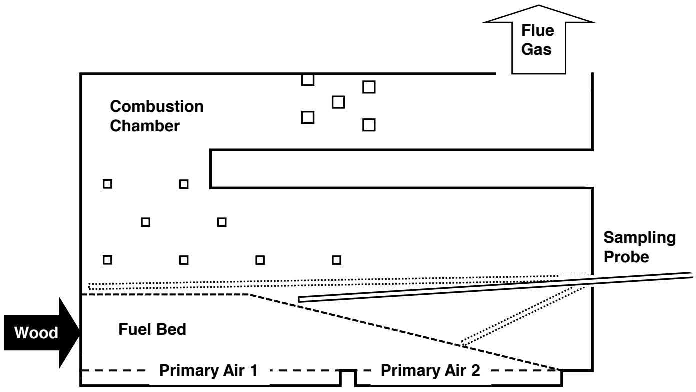

Figure 1: Schematic view of the 1.2 MW moving grate boiler with sampling probe for pyrolysis gases above the grate (displayed in three locations)

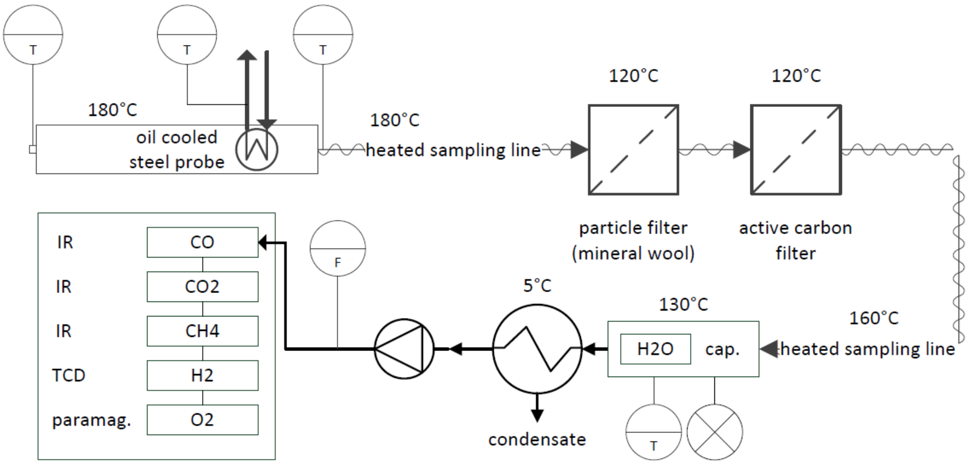

Figure 2: Experimental setup for gas sampling and analysis

After sampling, the gas passes a particle filter and an activated carbon filter for tar removal. The resulting particle and tar free gas is analysed with a moisture sensor consisting of a capacitive H_2O sensor with a special coating over the sensor plates. The sensor is placed inside a sintered metal part to assure secure functionality.

After condensation of the moisture content, CO, CO_2, CH_4 are analysed by non-dispersive infrared (ND-IR) analysers, H_2 by a thermal conductivity detector (TCD) and O_2 with a paramagnetic sensor.

The H_2O concentration is measured as absolute value in the sampled gas in [g/kg]. By assuming an ideal gas, the concentration is calculated as follows:

$$H_2O_{abs} = \frac{p_{H2O}}{R_{H2O} \cdot T_{gas}}$$

With the law of Dalton the concentration of H_2O in the gas is:

$$c_{H2O} = \frac{H_2O_{abs} \cdot R_{H2O} \cdot T_{gas}}{p_{gas}}$$

where R_{H2O}=461.52 [J/kg K].

The temperature of the pyrolysis gas is measured with a k-type thermocouple located at the tip of the probe.

2.4 Analysis of flue gas and operation conditions

During the tests, the main control parameters from the boiler as well as the flue gas properties, i.e., O_2, CO_2, CO, and T are recorded. The gas velocity in the combustion air supply channels used as a control parameter by the boiler, is measured with heated wire anemometry.

2.5 Experimental procedure

For sampling the gases, the steel probe is introduced into the combustion chamber through a hole in the front door. On the defined measuring points, the probe is put on top of the bed and then lifted to enable gas sampling slightly above the fuel bed. In each position, the sampling is performed during 10 minutes to minimise the influence of oscillation of the gas concentration induced by the grate movement.

Gas sampling is performed at maximum 11 positions along the grate, starting from 0.1 m distance from the fuel feed to the grate to the very end of the grate at 2.1 m from the fuel feed side.

3 MODELLING

For the gas flow and combustion modelling in the gas phase, the CFD software CFX 13.0 is used with the standard k-ε model for turbulence. Radiation is modelled with the discrete transfer model (DTM).

For turbulent combustion, the eddy dissipation model (EDM) with a product limitation factor of A = 1 in combination with the finite rate model (FR) is used [3]. Several single step and multistep and reactions are used for the conversion of the different gas species.

As boundary condition, average gas profiles along the grate from current measurements and literature [4–7] are introduced. Based on this, a fully covered grate is investigated as Reference case (Fig. 3).

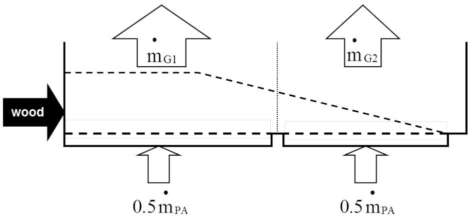

Figure 3: Modelling conditions for Reference case = fully covered grate with equal primary air in section 1 and 2.

To investigate the influence of the grate coverage, two cases of uncovered grate areas are introduced:

1. Grate coverage in direction of the grate length

   Here, a partly covered grate in the direction of the grate length with an uncovered section at the end of the grate is assumed (Fig. 4). For this case, the amount of leaking primary air (LPA) through the uncovered section 2 of the grate is varied, i.e., 20% and 30% of the total primary air is assumed to be injected through the uncovered section.

2. Grate coverage in direction of the grate width

   A partly covered grate with uncovered sections at the side walls (Fig. 5) is assumed. For this case, the uncovered area (A_u) is varied between 5% and 33% with LPA between 10% and 30%.

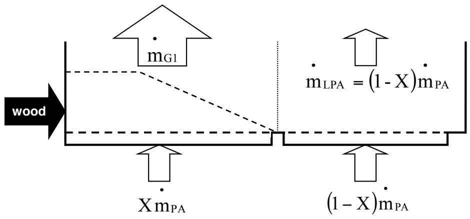

Figure 4: Modelling conditions for 57% covered grate. Distribution of fuel over the first grate section with uncovered second grate section and resulting Leaking Primary Air (LPA) in the uncovered grate

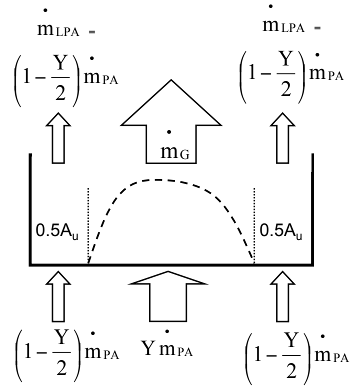

Figure 5: Primary air distribution for CFD modelling for uncovered grate area on the sidewalls and resulting leaking primary air (LPA)

4 RESULTS

4.1 Pyrolysis gas composition over the grate

Figures 6 and 7, in the lower figure, show the measured dry gas composition over the fuel bed for a covered and a partly uncovered grate respectively.

The gas composition above the fuel bed shows typical concentrations of CO, CO_2, H_2, and other compounds as found in biomass gasification [8,9]. In addition, a clear overlapping of the stages of drying, pyrolysis and char conversion is found, which is in line with investigations and models on solid fuel conversion [10,11].

On the first measurement point, located 0.1 m after the fuel feed to the grate, almost no pyrolysis gases are found. At this stage, the gas consists mostly of moisture, i.e., approx. 35%, and O_2 and CO_2, approx. 10%. With increasing grate length, pyrolysis gases are released from the fuel bed. Typically, the peak of H_2O can reach up to more than 50% based on wet gas and is found in a position at approximately 25% of the fuel bed length.

H_2 and CH_4 peaks occur at approximately 50% of the fuel bed length, indicating biomass gasification.

The CO peak is found in the second half of the fuel bed length, indicating char conversion.

The gas temperature varies by up to 700°C over the bed length. In the first half of the covered bed, temperatures as low as 200°C are possible due to heat up and evaporation of water from the wood chips. Maximum temperatures up to 1000°C occur in the second half of the covered grate where char conversion takes place.

It is clearly visible, that in case with an uncovered grate section at the end of the grate, the characteristic of the pyrolysis gas composition remains the same as in the reference case, but is moved more to the beginning of the grate.

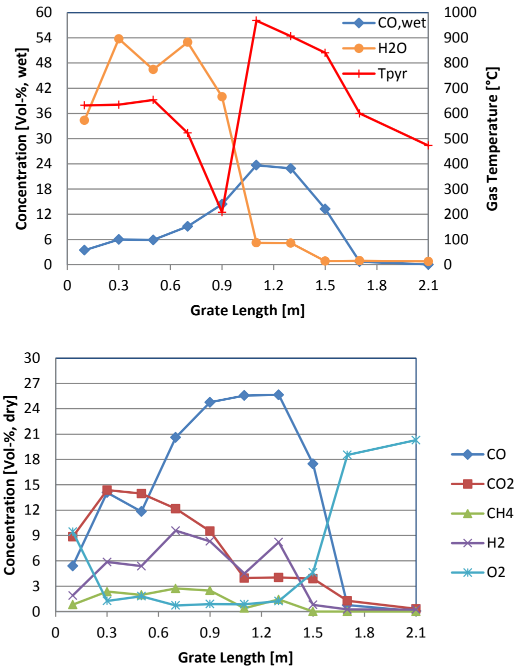

Figure 6: Gas temperature and H_2O and CO concentration in the wet gas (above) and pyrolysis gas concentration in the dry gas (below) for a covered grate

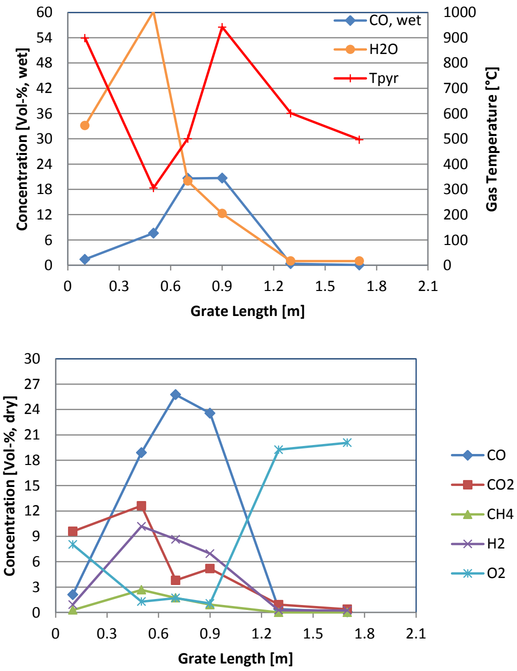

Figure 7: Gas temperature and H_2O and CO concentration in the wet gas (above) and pyrolysis gas concentration in the dry gas (below) for a partly uncovered grate

4.2 Grate coverage in direction of the grate length

4.2.1 CFD modelling

Fig. 8 shows the CO concentration from CFD calculations performed for the Reference case with fully covered grate. The gasification zone covers approximately 60% of the grate length. In addition, fast oxidation of CO takes place starting in the first section of the boiler above the grate and reaching near-complete combustion in the post combustion chamber.

Fig. 9 shows the calculated CO concentrations in case of 43% uncovered grate area at the end of the grate (primary air zone 2). In comparison to the covered grate, the gasification section is significantly shorter. In addition, strongly increased streak of air from the second half of the grate flows directly from the uncovered grate section to the post combustion chamber. High CO concentration is found at the entrance of the post combustion chamber. This is due to CO streaks entering the displayed plane in Fig. 9 from the side walls. Due to these CO streaks in the post combustion chamber, the final CO concentration in the flue gas is significantly higher than in the reference case (Fig. 8), as found by integration of the flue gases in the boiler exit.

Consequently, increasing CO emissions are expected with decreasing grate coverage due to non-ideal flow conditions.

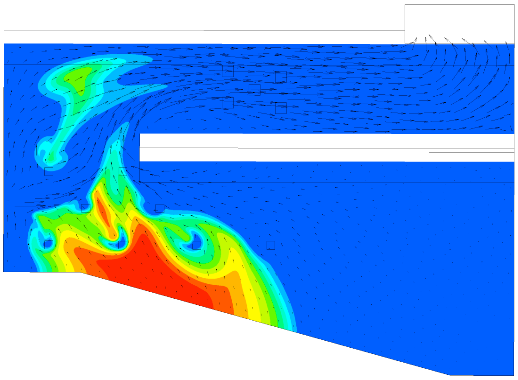

Figure 8: Calculated CO concentration above the grate and in the combustion chamber (red = high, blue = low) for the reference case (fully covered grate with equal primary air in zone 1 and 2)

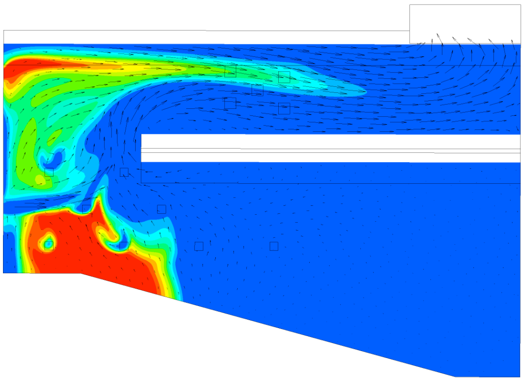

Figure 9: Calculated CO concentration above the grate and in the combustion chamber (red = high, blue = low) for the case with uncovered zone 2 and 20% leaking primary air through zone 2

4.2.2 Experiments on a 1.2 MW grate boiler

Experiments with partly uncovered grate are performed by increased primary air injection through the first grate zone at constant total primary air. Consequently, leaking primary air (LPA) occurs in the second section.

Fig. 10 shows the CO concentration as function of the grate coverage. Fig. 11 shows the excess air ratio found as function of the grate coverage due to the above described influence of leaking primary air. To describe the grate coverage, a measured O_2 concentration of $O_2 > 15$ vol.-% above the grate is defined as uncovered for the data analysis. Visual inspection of the grate is performed to confirm the threshold between covered and uncovered grate, which, however, is not a precise value.

With these limitation of the accuracy, the results in Fig.°10 show, that an increase of the uncovered grate area leads to an increase of the CO concentration. During ideal operation, an average excess air of $\lambda = 1.7$ with a CO concentration of 17 mg/m^3 at 11 vol.-% O_2 is found. This operation results in a grate coverage of 0.81 defined by $O_2 > 15\%$. Hence GC = 0.81 describes a well covered grate with high ash burnout quality, while GC > 0.8 would result in high unburnt carbon in the grate ash.

During operation with partly uncovered grate, the excess air ratio increases to $\lambda = 2.0–2.1$. An uncovered grate area of 40% leads to CO > 100 mg/m^3, and an uncovered grate area of 60% leads to CO > 200 mg/m^3 at 11 vol.-% O_2. Since the CO content in the flue gas is strongly influenced by the excess air ratio [2], the CO increase found here cannot be solely correlated with the grate coverage. Consequently, results at equal excess air are used to identify the influence of the grate coverage and to compare experimental results with CFD modelling. For this purpose, data from experiments and CFD calculations are compared at $\lambda = 1.8$, which in the present test runs resulted in CO = 25 mg/m^3 at 11 vol.-% O_2.

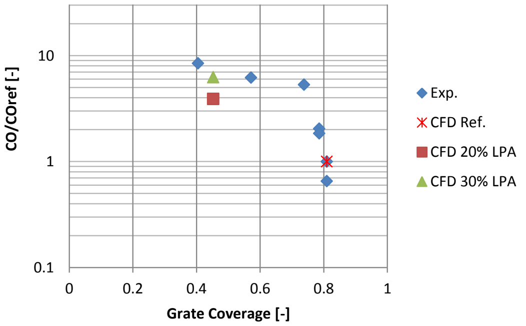

Figure 10: Average values of CO concentration in the flue gas during test runs as function of grate coverage, compared with CFD results for 20% and 30% leaking primary air (LPA)

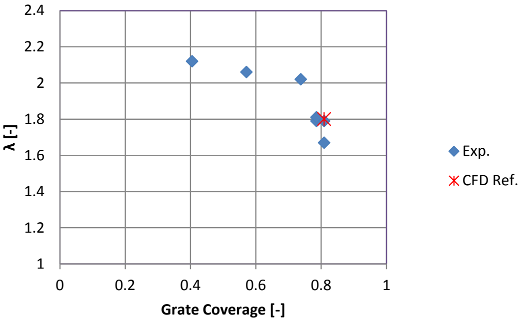

Figure 11: Excess air ratio as function of grate coverage

4.2.3 Comparison of experiments and CFD

Fig. 12 shows the factor of increase between CO in the flue gas and CO_{ref} as function of the excess air ratio defined as:

$$f = \frac{CO}{CO_{ref}}$$

where CO_{ref} = CO at $\lambda = 1.8$ and
at GC = 0.81 (ideally covered grate)

here $CO_{ref} = 25$ mg/m^3 at 11 vol.-% O_2

Two levels of grate coverage are shown with GC = 0.81 describing ideal operation and GC = 0.41 describing 60% uncovered grate area. As described in 4.2.2, the uncovered grate is related to an increased excess air ratio.

Results from experiments at high and low grate coverage at $\lambda = 1.8$ and slightly higher show a CO increase by a factor of approximately f = 2.5.

CFD calculation performed at $\lambda = 1.8$ reveal an expected CO increase by a factor 3.9 with 20% leaking primary air (LPA) and 6.2 for 30% LPA respectively.

During the experiments, LPA is estimated to be 21% for the case with GC = 0.41. Consequently, the qualitative effect of CO increase due to uncovered grate as expected from CFD is confirmed by the measurements, but the increase factor calculated in the simulations is slightly overestimated.

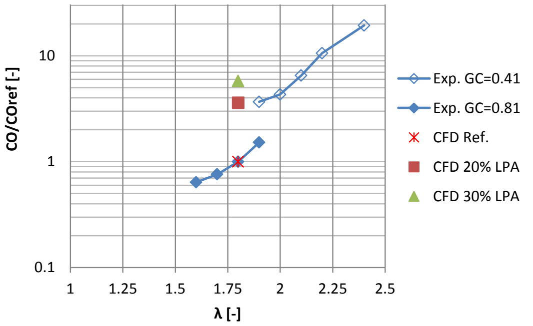

Figure 12: CO/CO_{ref} from experiments and CFD modelling as function of the excess air ratio for two levels of grate coverage, i.e., GC = 0.41 and GC = 0.82

4.3 Grate coverage in direction of the grate width

Depending on the grate design, primary air leakage can occur at the side walls to a certain extent. CFD calculations were performed to investigate the influence of air leakage at the side walls on the CO concentration in the flue gas with variation of air leakage from 10% to 30% of the total primary air and introduced to an uncovered grate area of 5% to 33%. Due to the disturbance of the flow fields, an effect on the CO concentration is found for all cases of air leakage at the side walls. However, there is no clear tendency to increasing CO with increasing air leakage. While low air leakage resulted in slightly improved combustion quality, high air leakage resulted in increased CO, with a maximum increase factor of f = 1.2 for 30% LPA.

5 CONCLUSIONS

Uneven fuel distribution is often observed in practical operation of grate boilers and assumed as a potential reason for increased emissions. Uneven fuel distribution can occur in different modes, e.g., uncovered sections at the end of the grate, partly covered sections at the side walls of the grate, or local channelling in the fuel bed. The focus of the present study is the influence of uncovered areas at the end of the grate, which is investigated by experiments on a 1.2 MW grate boiler and by CFD calculations leading to the following conclusions:

- In experiments on the grate boiler with different grate coverage situations varying from ideally covered grate with grate coverage GC = 0.8 to less than half covered grate with GC = 0.4 a significant influence of the grate coverage on the flue gas emissions is found.
- Due to the control type and changing boundary conditions during practical operation of the boiler, the variation of the bed coverage also influences the excess air ratio, since primary air leakage through uncovered grate sections causes increased oxygen content in the flue gas.
- To identify the specific influence of the grate coverage, data at equal excess air ratio of $\lambda = 1.8$ are compared. These experiments show, that the CO-concentration in the present experimental setup (from being 25 mg/m3 at 11 vol.-% O2 at good conditions) increases by a factor of 2.5 for an increase of the uncovered grate area from ideally covered to 60% uncovered.
- CFD calculations for identical conditions as during operation at $\lambda = 1.8$ result in a predicted CO increase by a factor of f = 3.9. Hence the negative effect of uncovered grate sections on the combustion quality is qualitatively confirmed by the experiments. The CFD modelling leads to slightly overestimated differences between ideally covered and highly uncovered grates.
- For uncovered grate sections at the side walls, the simulation predicts an effect of primary air leakage at the side walls with a slight increase of CO for high air leakage at the side walls. However, for low air leakage at the side wall, a slight improvement of the combustion quality is found. Compared to the influence of the bed coverage over the bed length, the influence of air leakage at the side wall is assumed to be less important in practice.
- To describe the grate coverage in practice and to derive input data for the CFD calculations, pyrolysis gas measurements are performed. For this purpose, gas sampling with an oil tempered steel probe is applied and confirmed as a valuable method to measure the gas concentration of CO, CO_2, CH_4, H_2, O_2 and H_2O. Among the gas species, the analysis of H_2O is essential due to high concentrations and high gradients over the grate.

6 OUTLOOK

Although a principal influence of uncovered grate sections on the combustion quality is confirmed, the presented findings are valid for the investigated boiler type under the described conditions and hence not applicable in general. Furthermore, the results depend on the introduced definition of grate coverage. More detailed information on the effects is of interest for further improvements of boiler design and operation:

- Information on the influence of uncovered grate sections on the emissions is scarce. Although the present investigation reveals that uncovered sections can lead to increased emissions, the variation of the grate coverage is not independent from other operation parameters. In the present experimental setup, the excess air ratio is influenced by the grate coverage due to the specific settings of the combustion control applied during the test runs. Further experiments at nearly constant excess air ratio can improve the quantification of the isolated influence of the grate coverage on the combustion quality.
- Besides uncovered grate sections at the end of the grate, other uneven fuel distribution situations are of interest (e.g. channelling and side wall effect). In addition other effects for uneven fuel distributions such as fast variations in fuel moisture or fuel size or fast changes of heat output (part load conditions) are of interest for future concepts to improve operation of grate boilers in practice.

To further improve the combustion quality of grate boilers in practice, the following concepts are proposed:

- The combustion control systems can be improved to maintain constant fuel bed conditions on the grate (as a primary measure) and/or to minimise negative effects of uneven fuel distribution on the grate (as a secondary measure).
- To reduce the influence of grate coverage on the combustion, improved design of the secondary air injection and the post combustion chamber design is proposed and investigated as primary measure by CFD and experimental validation of the fluid flow with particle image velocimetry (PIV) [12].

7 REFERENCES

[1] S. Van Loo, J. Koppejan, *The Handbook of Biomass Combustion and Co-firing*. 2008: Earthscan, London.

[2] T. Nussbaumer, Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction. *Energy Fuels*, 2003. 17(6): pag. 1510-1521.

[3] C. Bruch, T. Nussbaumer, CFD Modeling of Wood Furnaces. Biomass for Energy and Industry. *10th European Conference and Technology Exhibition*, June 8 – 11 1998, Würzburg, Germany, pag. 1366 – 1369

[4] B. Peters, Measurements and Application of a Discrete Particle Model (DPM) to Simulate Combustion of a Packed Bed of Individual Fuel Particles, *Combustion and Flame*, 131 Vol. (2002), pag. 132

[5] B. Olanders, N.-E. Gunners, Some Aspects of the Formation of Nitric Oxide During the Combustion of Biomass Fuels in a Laboratory Furnace, *Biomass and Bioenergy*, 6 Vol. (1994), pag. 443.

[6] H. Mätzing,H.J. Gehrmann, T. Kolb, H. Seifert, Experimental and Theoretical Investigation of Biomass Conversion in a Fixed Bed, *International Conference on Thermal Treatment Technologies and Hazardous Waste Combustors (IT3),* San Francisco, California, May 17-20, 2010

[7] T. Klasen, K. Görner, Numerical Calculation and Optimisation of a large Municipal Solid Waste Incinerator Plant, *2nd Int. Symposium on Incineration and Flue Gas Treatment Technologies*, University of Sheffield, UK, 4–6 July 1999.

[8] T.B. Reed, Biomass Gasification: Principles and Technology. *Energy Technology Review*. Vol. 67. 1981: Noyes Data Corporation.

[9] H. Hofbauer, M. Kaltschmitt, 10.1 Vergasung, *Energie aus Biomasse*, Springer 2001, pag. 427–505.

[10] Y.B. Yang; R. Newman; V. Sharifi; J. Swithenbank; J. Ariss, Mathematical modelling of straw combustion in a 38 MWe power plant furnace and effect of operating conditions, *Fuel*, Vol. 86, Issues 1–2, January 2007, pag. 129–142

[11] H. Thunman, B. Leckner, Ignition and propagation of a reaction front in cross-current bed combustion of wet biofuels; *Fuel*, 2001, pag. 473-481

[12] M. Baillifard, E. Casartelli, Th. Nussbaumer, Experimental Investigation of the Fluid Dynamics in Wood Combustion Processes, *16th European Biomass Conference and Exhibition*, Valencia, 2–6 June 2008, ETA-Florence

8 ACKNOWLEDGMENTS

Innovation Promotion Agency (CTI)
SCHMID energy solutions, Eschlikon