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Detailed Operational Mapping of a Grate Fired Biomass Combustion Plant for Improved Combustion Process Control

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Biomass combustion plants in Norway are facing stricter emission regulations and lower profitability, mostly due to low energy prices. Hence, performance optimization through improved combustion process control and/or retrofitting becomes very attractive to existing plants. However, the trial and error approach usually applied by the plant operator is time and cost consuming, and offers no guarantee of success. Increased combustion process knowledge on the other hand has the potential to provide the necessary input to improved combustion control strategies. The outcome of the improved control strategies can be lower emission levels, improved efficiencies, increased plant capacity or/and reduced maintenance costs. In this study, a measurement campaign was carried out at a 10 MW grate fired plant burning wood briquettes. The aim of the measurement campaign was to map the concentrations of a number of gaseous species inside the combustion chamber, at different locations and at varying operating conditions. Together with continuously measured flue gas concentrations and plant operational data, the measurements provide valuable information for combustion control strategies as well as for validation of modelling approaches, or input to these. Computational Fluid Dynamics (CFD) is the ultimate design tool for bioenergy plant combustion and heat transfer sections, however, cost-effective sub-models need to be developed. The measurement campaign carried out provides useful data for CFD modelling of the plant, both for modelling of the fuel bed, the freeboard and flue gas emission levels.

1. Introduction

Due to its low contribution to the greenhouse gas emissions, biomass is a good alternative to fossil fuels. However, biomass may possess properties that can make it challenging to convert into useful energy. For instance, biomass can be heterogeneous in nature which can lead to unstable conditions during thermal conversion. Unstable conditions can lead to increased emissions of products of incomplete combustion such as particles, carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAH), etc. Other challenging aspects are ash sintering, agglomeration, fouling, deposit formation and high temperature corrosion where the severity of these depends on both the ash content of the feedstock and the presence of certain elements such as alkali metals and chlorine. A comprehensive presentation of challenges and remedies related to biomass combustion can be found in the work of (Khan et al., 2009) while chlorine corrosion in boilers are explained in details in (Nielsen et al., 2000). Another challenge related to the combustion of biomass is the relatively high nitrogen content of the feedstock which leads to NO_X emissions. Among the different NO_X forming mechanisms; thermal NO_X, prompt NO_X and fuel NO_X, the latter is the predominant mechanism in biomass combustion. An in-depth presentation of NO_X formation mechanisms can be found in (Glarborg, 2003) while primary measures for reducing NO_X emissions can be found in (Nussbaumer, 2003). NO_X emissions in Norway are restricted through tight regulations (utterly sharpened in 2015) as shown in Table 1 (LOVDATA, 2015). The values in Table 1 have undergone several revisions through the years, resulting in stricter regulations. For this reason, plant owners are anticipating even stricter regulations in the future and are

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therefore interested in fine tuning their plants to reduce their emissions in a cost-efficient manner. In addition, plants with capacities above 10 MW have to pay an excise duty to the State Treasury - amounting to 19.19 kroner per kg for emissions of NOx (Avgiftsdirektoratet, 2015).

Table 1: Emission limits for clean biomass-fired heat/CHP plants. Values are normalized to dry basis and for an oxygen concentration of 6 vol. % in the flue gas

Capacity	Particles mg/Nm³ 12 hours average values	NOx mg/Nm³ one hour average	CO mg/Nm³ one hour average
1 < 5 MW	225	-	200
5 < 20 MW	75	300	200
20-50 MW	30	300	150

In Norway grate fired boilers using wood chips or by-products from sawmills are commonly used for district heating. These plants operate with very low profit margins which makes it quite challenging to meet new emission regulations. Such plants will hardly survive economically in case they are forced to invest in complex gas cleaning systems and hence have to solely rely on primary measures for emission control. Strategies for controlling emissions in a biomass grate-firing boiler can be found in (Yin et al., 2008a), while (Houshfar et al., 2012) shows the benefits of staged combustion on NO_X emissions in a lab scale reactor. Computational Fluid Dynamics (CFD) is therefore a useful tool in order to optimize operational parameters in a combustion plant. However, such a tool will be more beneficial as a prediction tool whenever models are developed using experimental data from measurements close to the fuel bed. There are a handful of publications that attempt to combine direct measurement for the validation or development of CFD models in grate fired boilers, among these are the studies by (Zhang et al., 2010), (Yin et al., 2008b) and (Li et al., 2009). Lately, similar work was performed in a reciprocating-grate fired boiler by (Sefidari et al., 2014) and (Razmjoo et al., 2014). Sefidari and Razmjoo focused on the detailed mapping of NO_X emissions above the grate; however nitrogen precursors such as NH_3 and HCN were not measured. This work attempts at measuring both minor and major gaseous species inside the combustion chamber of a grate fired boiler. The purpose of these measurements is to provide reliable data for modelling of this boiler, which can be used at a later stage for improving its performance.

2. Materials and methodology

2.1 Description of the grate fired boiler

Measurements are conducted in a grate fired boiler with a nominal capacity of 10 MW. The Marienborg plant is owned by Statkraft and is located in Trondheim, Norway. Figure 1 shows a schematic of the furnace which includes a reciprocating grate and is divided into the primary and the secondary combustion chamber. The primary air is introduced through four wind-boxes beneath the grate and enters into the bed through the space between the grate bars. The secondary air is injected through ports placed above the bed and in the front and back walls of the furnace. Additionally, exhaust gas from the outlet of the boiler is recirculated through the primary and secondary air ports to control the local temperature. The bottom ash is collected in the ash box at the lower end of the grate.

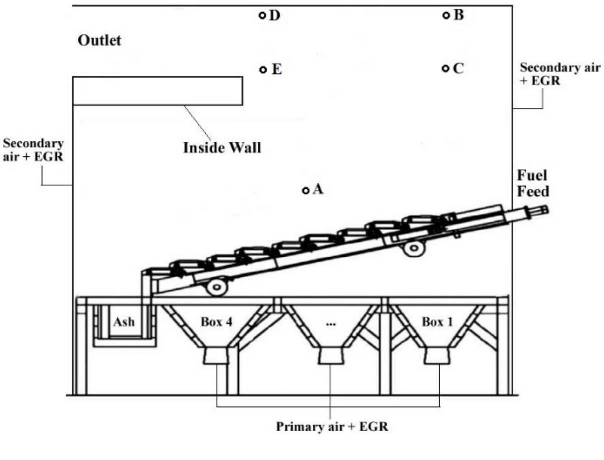

Figure 1: Schematic of the Statkraft Marienborg furnace (Trondheim, Norway) & the measuring positions.

As also shown in Figure 1, from the viewpoint of the side walls, the measurement positions are labelled A, B, C, D, and E. ‘A’ is located just above the fuel bed and is accessed from the side of the combustion chamber where the probe is pushed as far as possible inside the chamber (approximately 2 meters relative to the outer wall). 'B' and 'C' are accessed through the same port located at the upper corner of the combustion chamber. 'D' and 'E' are accessed through another port from the top located close to the furnace exit. The position of 'D' and 'B' is approximately 10 cm below the top inner wall of the combustion chamber. The distance is calculated relative to the tip of the suction probe inside the combustion chamber. The position of 'E' and 'C' are 90 cm below the top inner wall.

2.2 Experimental equipment and analytical methods

The suction probe used was especially designed to extract gas samples from the inside of the combustion chamber. The probe is 2.5 meters long, made of titanium shields inside an electrically heated line to prevent the sampled gas from over-cooling. The heating probe is water cooled for heat protection. In order to remove the entrained particles in the sample gas, a customized filter line was constructed and is shown in Figure 2. The heating line is composed of three filters mounted in series with heating hoses after which a pump is placed. The first filter is a glass wool filter with a high filtering capacity, cleaning the gas from the larger particles. The two other filters are a stainless steel filter and a ceramic filter with respective porosities of 3 and 2 μm. All components, including the pump, are electrically heated to a temperature of 180 °C. The precise temperature control makes sure that no component in the flue gas is lost to condensation or adsorption. This complex system is necessary especially for measuring NO_X precursors, NH_3 and HCN. The probe is inserted into the furnace through the measuring ports and positioned at the locations indicated in Figure 1. The measurements for each position are carried out continuously for 2-4 hours. Water cooling of the sampling gas is sufficient for stopping further reactions inside the probe. The quenched gas from the probe is cleaned by the filters and then analysed using both FTIR and GC. Deposits of fly ash particles and condensed tars will rapidly clog the probe and filters, thus, they are cleaned frequently by blowing pressurized air through the entire line.

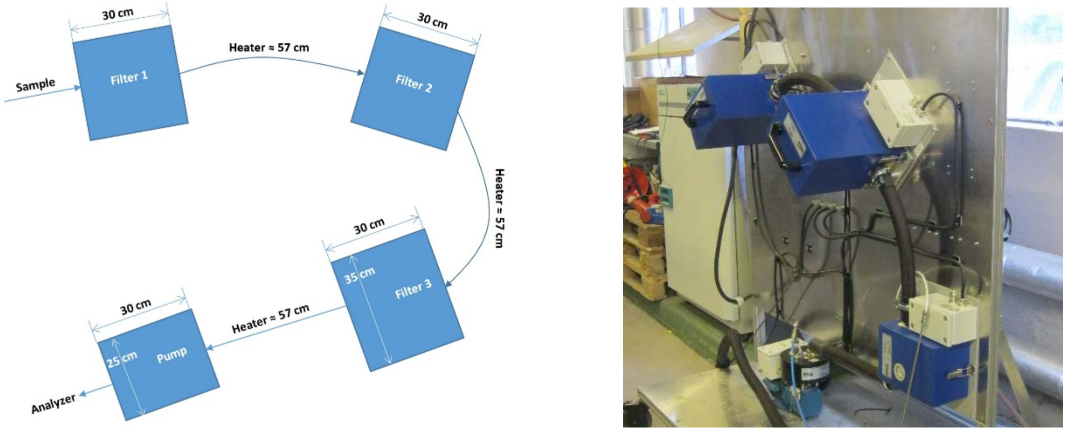

Figure 2: Particle filters: (a) the schematic, and (b) the real setup.

2.3 Experimental conditions

The biomass fuel is spruce wood briquettes and the proximate and ultimate analyses of the fuel are shown in Table 2. The combustion load was varied in the range of 4.5-10.5 MW during the measurement campaign.

Table 2: Proximate and ultimate analyses of the fuel (wt. %) according to ASTM standards

Proximate analysis (as-received)				Ultimate analysis (daf. basis)				HHV (MJ/kg)
Moisture	Ash	Volatile matter	Fixed carbon	C	H	N	O	
7.19	0.17	79.91	12.73	50.85	6.10	0.08	42.97	20.5

3. Results and discussion

In order to report its emissions to the competent authorities, the plant carries out gas measurements prior to the stack. Among measured compounds are CO, O_2, NO_X and particles. Selected emission data from the plant are presented in Figure 3, as a function of O_2 concentration (left hand side) and plant thermal load (right hand side). Each plotted point represents an average value for one hour. It is important to mention that as the thermal load of the plant is varied, the distribution of combustion air inside the boiler is automatically regulated. The oxygen concentration for the relevant period varied between 6 – 7 %. As the oxygen concentration increases in the flue gas the emissions of NO_X, CO and particles are all decreasing. In general the products of incomplete combustion tend to have an opposite trend relative to NO_X and combustion air. However, for this boiler the emissions seem to be controlled through the automated air distribution system which regulates the distribution of the combustion air inside the boiler. The thermal load increase, as can be seen from the right hand side of Figure 3, is contributing to the increase of all the measured compounds. The increase in NO_X could be explained by some local temperature increase inside the boiler. For CO and particles the temperature increase should result in lower emissions. However, this is offset by lower residence time inside the boiler and in case of particle emissions, more entrainment due to the increased gas velocities.

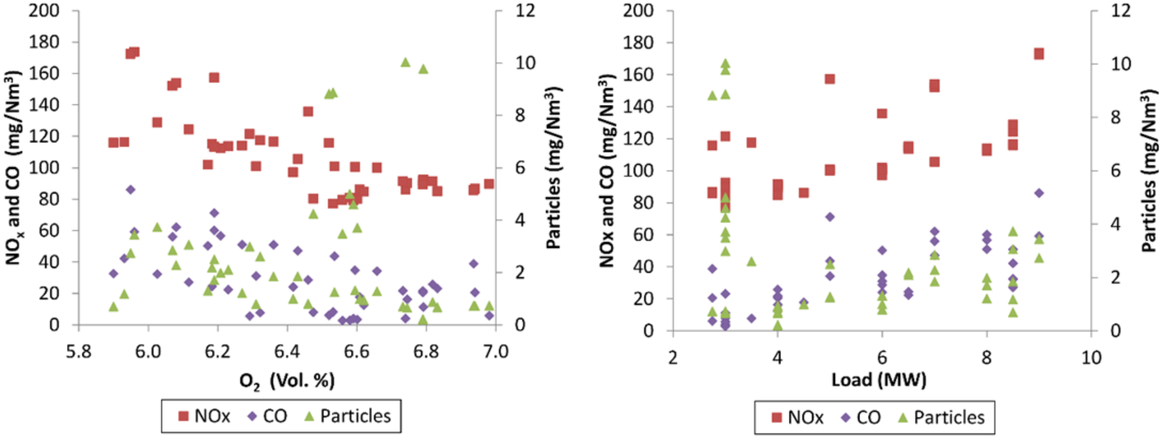

Figure 3: Pollutants routinely measured by the plant operator during the experimental campaign, data points are one hour averages taken prior to the stack and on dry basis.

The gas concentrations above the fuel bed as a function of thermal load are shown in Figure 4, revealing the early stages of the thermal conversion process. The left hand side of the figure shows the products of incomplete combustion while the right hand side figure shows the NO_X precursors NH_3 and HCN. The probe for these measurements is positioned just above the fuel bed. However, due to variations in fuel bed thickness, it is difficult to estimate the vertical distance between the bed and the probe. The oxygen concentration above the bed varied between 3 and 9 vol. %, which means that not all the oxygen provided from underneath the bed was able to react at the point of gas extraction. All the products of incomplete combustion are increasing with increased thermal load. This is due to increased devolatilization, mainly caused by the increased fuel amount on the bed. It is also interesting to notice the linear correlation between the concentrations of devolatilized products above the bed. Figure 5 shows the linear dependency of both CO and CH_4 on C_2H_2. The concentration of HCN is approximately 10 mg/Nm^3 at 4.5 MW load and increases to ca. 25 mg/Nm^3 at 10.5 MW. The ammonia concentration is very low for all the measurements made. One reason for this could be adsorption in the filter line due to cold spots, which may occur despite all the measures that were taken to avoid it.

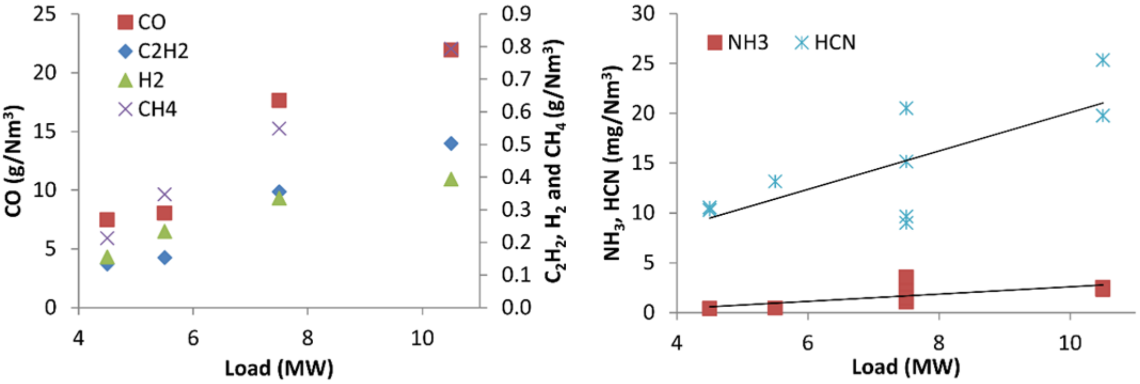

Figure 4: Gas measurements taken at port A, above the fuel bed and as a function plant load. Products of incomplete combustion (left hand side) and NO_X precursors (right hand side).

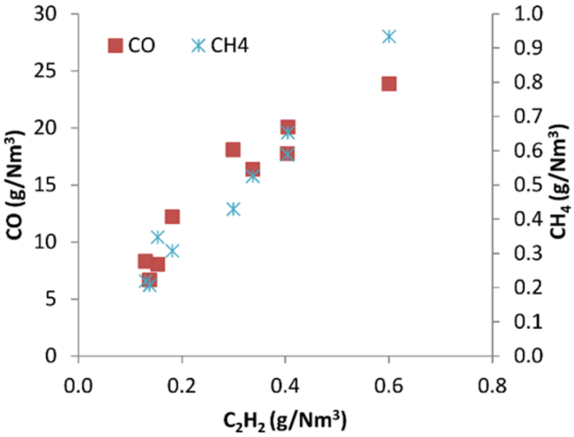

Figure 5: Linear dependency of the devolatilised products measured above the bed.

Figure 6 shows the NO and CO concentrations at positions B, C, D and E, for the thermal loads 5.5, 7.5 and 10.5 MW. The concentration of NO is stable at 50 – 60 mg/Nm^3 at all loads and also at the different positions. For CO, there are large variations: a 20-fold increase is observed at 5.5 MW compared to higher loads. Furthermore, there are large concentration variations between B and C which uses the same port with C being deeper inside the boiler compared to B. Measurement at positions D and E were only performed at the lowest load. However, Figure 6 shows that CO concentrations are very low which indicates that the combustion at this stage is complete.

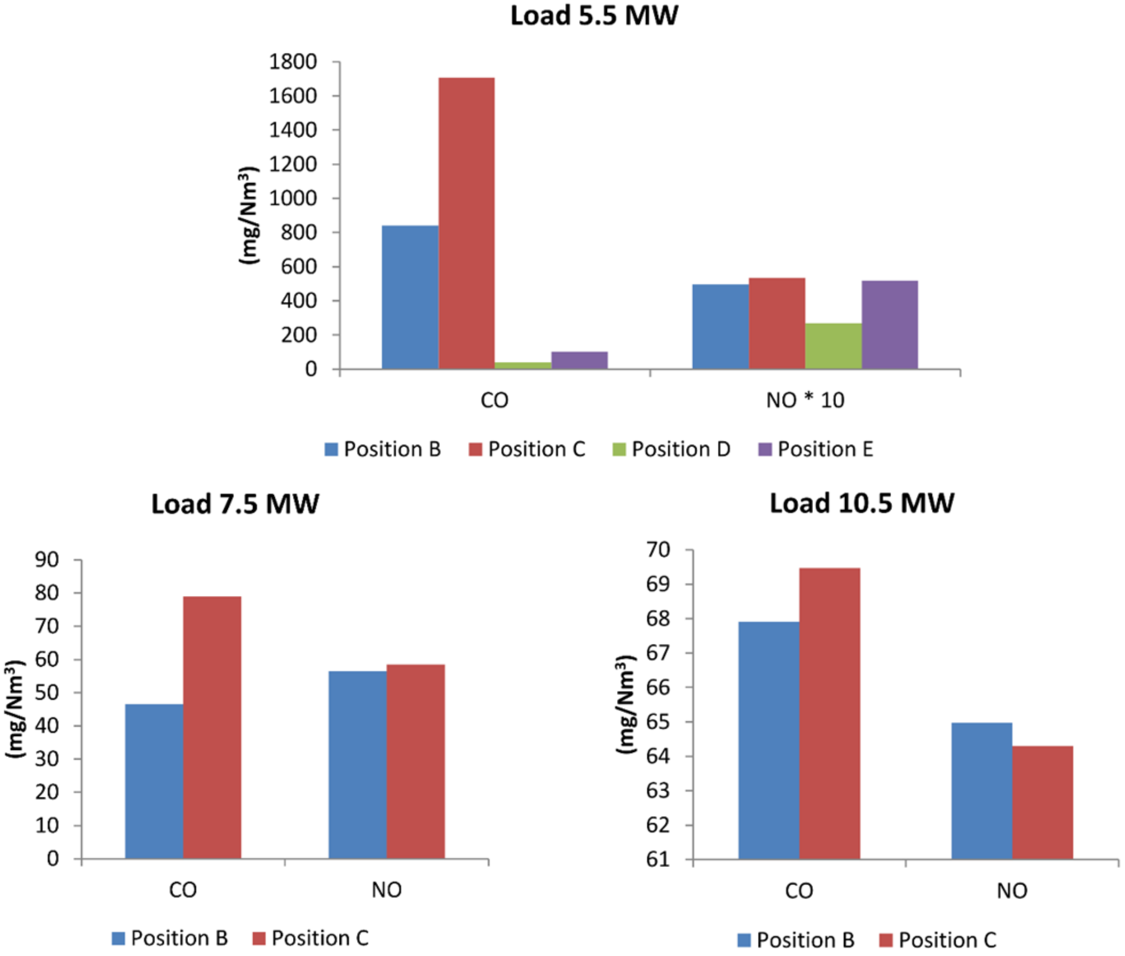

Figure 6: CO and NO concentrations for positions B, C, D and E at different plant loads.

4. Conclusions

Gas measurements at different locations inside a reciprocating grate boiler were performed with the intension of understanding better the combustion process in order to improve performance through primary measures. The collected data will also be used for the validation of a CFD model that is currently under development. The measurements taken just above the bed showed high concentration of devolatilization products. These products increased with increasing thermal load. Also the NO_X precursors HCN and NH_3 increased with increasing load. However, the measured ammonia concentration was lower than expected and could be caused by adsorption in the filter unit. Gas measurements were also taken after secondary air injection (positions B and C) and at the outlet of the combustion chamber (positions D and E). For low thermal load, unburnt compounds were still present at position B and at even higher concentrations further inside the boiler (position C). This is reflected by the high CO concentration. Higher thermal load resulted in better combustion efficiency, however the CO concentration still increased when the probe was positioned further into the boiler (positions E and C). NO concentrations at all these positions (B, C, D and E) were stable.

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