Hesch Thomas, Biedermann Friedrich, Brunner Thomas, Obernberger Ingwald, 2011: Reduction of NOx and PM1 emissions from automated boilers by advanced air staging. In: Proceedings of the 19th European Biomass Conference & Exhibition, June 2011, Berlin, Germany, ISBN 978-88-89407-55-7, pp. 874-879, ETA-Renewable Energies (Ed.), Italy

# REDUCTION OF $NO_X$ AND $PM_1$ EMISSIONS FROM AUTOMATED BOILERS BY ADVANCED AIR STAGING

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ABSTRACT: This paper presents the possible reduction potential of $NO_x$ and $PM_1$ emissions by applying advanced air staging. Test runs with chipboard have been carried out with a 150kW pilot-scale furnace with moving grate technology. The influence of the air ratio in the primary combustion chamber, the temperature in the primary combustion chamber, the residence time in the primary combustion chamber, the type of the flue gas recirculation and the boiler load on $NO_x$ and $PM_1$ emissions have been evaluated. The results showed that the $NO_x$ emissions are mainly influenced by the air ratio in the primary combustion chamber. An optimum can be observed at an air ratio between 0.9 and 1.0. Furthermore, $NO_x$ emissions decrease with decreasing temperature and increasing residence time in the primary combustion chamber. In addition, also the temperature in the primary combustion chamber and the type of flue gas recirculation seems to have a certain effect on $NO_x$ emissions. Regarding $PM_1$ emissions, the following two influencing parameters are of most relevance: the volume flow of the gas through the fuel bed (cooling effect) and the temperature in the primary combustion chamber. Additional test runs with wood chips and short rotation coppice to evaluate possible influences of different fuels are foreseen.
Keywords: combustion, $NO_x$ emission, particle emission, pilot-plant, air staging, primary measures

## 1. INTRODUCTION AND OBJECTIVES

Biomass offers the greatest potential for the generation of heat and power of all renewable energy sources (except hydro power). Furthermore, biomass is the only renewable energy source, which can absorb $CO_2$ directly from the atmosphere and therefore contributes directly regarding $CO_2$ reduction. However, the combustion of biomass also results in the emission of air pollutants such as CO, OGC, $NO_x$ and $PM_1$. Modern biomass furnaces show already low CO and OGC emissions which indicate a complete burnout but the $NO_x$ and $PM_1$ emissions are still too high. The $NO_x$ emissions of biomass combustion are formed mainly from the nitrogen that is contained in the fuel and depends on the operational conditions during combustion. Thermal and prompt $NO_x$ formation is negligible [1, 2].

Within the scope of the work presented the effects of different air staging strategies on $NO_x$ and $PM_1$ emissions have been evaluated. The results shall form the basis for the development of future low emission biomass combustion systems by efficiently applying primary measures.

Previous studies which summarize and evaluate data available regarding the influence of air staging on $NO_x$ and $PM_1$ emissions for fixed-bed biomass combustion have shown that up to now no reliable data are available regarding comprehensive systematic studies on air staging strategies [3, 4, 5, 6, 7]. In addition, previous studies do not consider false air streams. False air is air entering the furnace in an uncontrolled way mainly by leakages (e.g. due to untight fuel or ash transportation systems). These facts stress the importance of systematic air staging tests under consideration of false air.

Air staging means that the combustion air is induced into different zones of the combustion chamber. In modern biomass furnaces the combustion chamber is usually separated into a reduction zone where devolatilisation and an oxidizing zone where complete burnout of the flue gas takes place. Advanced air staging means that air staging takes place under well defined conditions and in a controlled way and that also false air and flue gas recirculation are considered in the overall concept. The total air ratio, the air ratio in the primary combustion chamber (PCC), the air ratio in the fuel bed and the temperature in the PCC (T_PCC) are adjusted by the amount of primary and secondary combustion air and the amount of flue gas recirculation (Rec.). The flue gas recirculation can be induced above the grate or below the grate which allows an individual adjustment of the air ratio in the PCC and the air ratio in the fuel bed. In addition, false air streams have to be minimized in order to implement an advanced air staging concept. An optimised and advanced air staging concept has the advantage that $NO_x$ and $PM_1$ emissions can be reduced only by applying primary measures and additional secondary measures can often be avoided.

This paper presents the effect of the air ratio in the PCC, the temperature in the PCC, the residence time in the PCC, the type of flue gas recirculation and the boiler load on $NO_x$ emissions. Moreover, the influence of the gas volume flow through the grate, the air ratio in the fuel bed and the temperature in the PCC on $PM_1$ emissions is investigated.

## 2. METHODOLOGY

In a first comprehensive test series, the combustion behaviour of chipboard has been examined. Chipboard from the same production patch and no chipboard residues has been used for the entire test series in order to ensure uniform fuel quality and composition.

The element content of the fuel has been determined by wet chemical analysis. The moisture content of the fuel has been measured according to ÖNORM CEN/TS 14774. Sample preparation has been carried out according to CEN/TS 14780. The ash content has been measured according to CEN/TS 14775 (determination of the loss of ignition at 550°C). The H-, C- and N-content of the fuel have been determined according to ÖNORM CEN/TS 15104 and the Cl-content according to ÖNORM CEN/TS 15289. Major and minor elements in the fuel have been measured according to ÖNORM CEN/TS 12290 and 15297.

**Nomenclature**

| | | | |
|---|---|---|---|
| ac | ash content | T_PPC | temperature in the primary combustion chamber |
| d.b. | dry base | TIC | total inorganic carbon |
| mc | moisture content | OGC | organic gaseous carbon |
| PCC | primary combustion zone | TSP | total suspended particles (total dust in the flue gas) |
| $PM_1$ | particulate emissions below 1µm | w.b. | wet base |
| Rec. | flue gas recirculation | wt% | weight percent |

Test runs have been performed at a pilot-scale combustion plant with a nominal boiler capacity of 150kW (Figure 1, number 8 und 9). The furnace is equipped with moving grate technology and the combustion chamber is geometrically separated into a PCC and a secondary combustion chamber. Secondary air can be induced at two different positions into the furnace in order to vary the residence time of the flue gas in the PCC (see Figure 1, number 5 und 6). The estimated residence time in the PCC at full load varies between 1 and 2 seconds for the large PCC and between 0.6 and 1.3 seconds for the small PCC depending on the air ratio in the PCC applied. The plant is equipped with flue gas recirculation, whereby the recirculated flue gas can be induced above or below the grate (see Figure 1, number 8 and 9). Fuel is supplied with a screw conveyer. False air (air leakages) in the furnace especially in the PCC through the fuel feeding system and the ash discharging system has been minimised in order to guarantee an effective air staging. In this respect it is important that the fuel feeding, the ash discharge channel and the furnace doors are tight and that there are no open holes in the furnace.

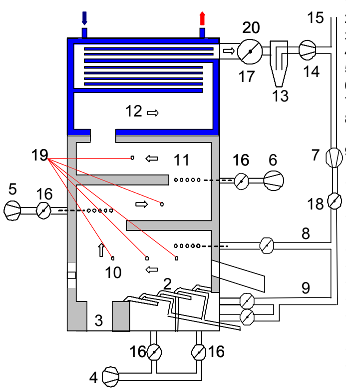


**Figure 1:** Scheme of the 150kW plant equipped with moving grate technology including measurement setup

During the test runs performed all combustion air, flue gas and flue gas recirculation flows as well as the gaseous emissions (CO, $CO_2$, $O_2$, NO, $NO_2$) at boiler outlet have been continuously measured. In addition all relevant plant operation parameters such as load, temperatures, etc. have been recorded. Furthermore, the $PM_1$ and TSP emissions have been measured at boiler outlet in periodic intervals. The measurement setup is illustrated in Figure 1.

The combustion air flows have been measured with hot wire anemometers (Type: Bosch HFM-2C-4.7) and the amounts of recirculated flue gas and the flue gas downstream the boiler have been measured with Prandtl tubes. A Rosemount NGA 2000 gas analyser has been used for the determination of the gaseous emissions of CO, $CO_2$ and $O_2$. NO and $NO_2$ have been measured with a CLD 700 EL ht gas analyser from the manufacturer ECO Physics. All temperatures have been recorded with type K thermocouples and the temperature at the end of the PCC has been additionally recorded with a suction pyrometer. The power has been recorded with a heat meter (Type: Viterra Energy Services Sensonic). $PM_1$ emissions have been measured with a Berner-type low-pressure impactor and TSP emissions with equipment according to VDI 2066.

Within the scope of the test runs performed the following influences on $NO_x$ emissions have been investigated:

- Air ratio in the PCC
- Temperature in the PCC
- Residence time in the PCC
- Type of flue gas recirculation (recirculation above or below the grate)
- Load

The air ratio in the PCC is defined as the ratio of the amount of oxidising agents supplied into the PCC (induced by primary air and flue gas recirculation) divided through the amount of oxidising agents needed for stoichiometric combustion. The air ratio in the fuel bed is defined as the ratio of the amount of oxidising agents supplied into the fuel bed (primary air supply and flue gas recirculation below grate) divided through the amount of oxidising agents needed for stoichiometric combustion and the total air ratio is defined as the ratio of the supplied amount of oxidising agents with the combustion air (primary and secondary air supply) divided through the amount of oxidising agents needed for stoichiometric combustion. The temperature in the PCC is defined as the temperature of the flue gas at the end of the PCC and the residence time is defined as the mean residence time in the PCC (volume of the PCC / volume flow of the flue gas in the PCC related to the temperature in the PCC).

In a first test series the influence of the air ratio in the PCC has been evaluated with flue gas recirculation above grate and a long residence time in the PCC at a temperature in the PCC of 1,000°C and a boiler load of 150kW (full load). For the next test series different operating conditions influencing $NO_x$ and $PM_1$ emissions have been adjusted (temperature in the PCC, type of flue gas recirculation, residence time in the PCC, temperature in the PCC, load) and again tests with varying air ratios in the PCC have been carried out. The results have been subsequently compared with the first test series (reference). The different operation conditions varied during the test series performed are shown in Table 1. In order to confirm the results, repeated test runs have been performed for selected operation conditions.

During the test runs the amount of primary air, flue gas recirculation and fuel feed were manually adjusted to the side constraints of the specific test run. Secondary air was automatically controlled by the standard control system of the plant.

The side constraints for all test runs performed have been determined with an in-house developed calculation program before the test runs started. This program calculates the needed amounts of primary combustion air, secondary combustion air and flue gas recirculation on the basis of mass and energy balances for a defined combustion condition (defined air ratio in the PCC, temperature in the PCC, boiler load and total air ratio). The plausibility of the calculation has been checked by comparing calculated with subsequently measured data.

**Table 1:** Matrix of the test series performed

| influencing parameter investigated [-] | air ratio in the PCC [-] | temperature in the PCC [°C] | size of the PCC [-] | flue gas recirculation type [-] | boiler load [kW] |
|---|---|---|---|---|---|
| air ratio in the PCC (reference) | varied | 1,000 | large | above grate | 150 |
| type of flue gas recirculation | varied | 1,000 | large | below grate | 150 |
| residence time in the PCC | varied | 1,000 | small | above grate | 150 |
| temperature in the PCC | varied | 900 and 1,100 | large | above and below grate | 150 |
| load | varied | 1,000 | large | above grate | 75 |

## 3. RESULTS

### 3.1 Fuel analysis

Table 2 shows the composition of the chipboard fuel used in comparison with database values. The N content varies between 3.6 and 3.8 wt% (d.b.) which is on the upper end of the database values and significantly higher than typical values for wood fuels (the average N content of wood chips with bark amounts to approx. 0.11 wt% d.b.). Due to the high N content of chipboard it is of great importance to operate a combustion plant under optimal air staging conditions to keep $NO_x$ emissions at a low level. The C, H, and ash contents are comparable with wood chips.

Chipboard has a low moisture content (<10 wt% w.b.) which leads to high combustion temperatures. Therefore, flue gas recirculation is needed in order to keep the temperature in the PCC acceptably low.

The sum of the major aerosol forming elements (K+Na+Zn+Pb) is comparable to wood chips. Hence, low $PM_1$ emissions can be expected. The 2S/Cl ratio is above 2 which indicates that more sulphates that chlorides are to be expected in the aerosols. Concluding, the chipboard fuel can be seen as representative.

**Table 2:** Fuel composition of the chipboard used and comparison with database values

| fuel | | chipboard | chipboard | chipboard - database values | | |
|---|---|---|---|---|---|---|
| analysis-no. | | 8,673 | 9,131 | min. | max. | no. of samples |
| mc | wt% w.b. | 9.1 | 6.9 | | | |
| gross calorific value | kJ/kg d.b. | 19,500 | 19,600 | 19,600 | 19,600 | 1 |
| ac | wt% d.b. | 0.88 | 1.20 | 0.52 | 1.49 | 6 |
| ac (without TIC) | wt% d.b. | 0.75 | 1.01 | | | |
| C | wt% d.b. | 47.4 | 48.0 | 47.7 | 51.2 | 17 |
| H | wt% d.b. | 6.2 | 6.0 | 5.4 | 7.3 | 17 |
| N | wt% d.b. | 3.6 | 3.8 | 2.4 | 3.6 | 17 |
| S | mg/kg d.b. | 322.0 | 179.0 | 151.0 | 630 | 5 |
| Cl | mg/kg d.b. | 285.0 | 191.0 | 123.0 | 1,250 | 5 |
| Si | mg/kg d.b. | 788 | 1,240 | 36.3 | 1,360 | 8 |
| Ca | mg/kg d.b. | 1,770 | 2,190 | 1,197 | 3,001 | 8 |
| Mg | mg/kg d.b. | 333.0 | 434.0 | 176.0 | 310.0 | 8 |
| K | mg/kg d.b. | 600 | 698 | 527 | 980 | 8 |
| Na | mg/kg d.b. | 192.0 | 232.0 | 90.9 | 301.0 | 8 |
| P | mg/kg d.b. | 73.1 | 76.0 | 142.0 | 149.0 | 2 |
| Zn | mg/kg d.b. | 60.7 | 42.0 | 15.6 | 64.3 | 8 |
| Pb | mg/kg d.b. | 9.4 | 5.0 | 1.73 | 61.0 | 5 |
| 2S/Cl | mol/mol | 2.5 | 2.1 | | | |
| K+Na+Zn+Pb | mg/kg d.b. | 862 | 977 | | | |

### 3.2 Results of the test runs performed – operating conditions

Regarding a correct assessment of $NO_x$ and $PM_1$ emissions a complete burnout is important since $NO_x$ and $PM_1$ emissions are affected by the burnout quality. The burnout quality is influenced by the furnace technology and by the total air ratio. An important indicator for the burnout quality are the CO emissions. Consequently, the dependency of the CO emissions on the total air ratio has been determined for full and for part load.

For total air ratios between 1.30 and 1.62 the average CO emissions measured were well below 100 mg/Nm³ (dry flue gas, 13%$O_2$) which proves that no effect of the burnout quality on $NO_x$ emissions can be expected.

The average CO emissions measured during all air staging test runs amounted to approx. 19 mg/Nm³; dry flue gas, 13%$O_2$ (standard deviation: 41 mg/Nm³). For the test runs performed the total air ratio has been adjusted to approximately 1.4. Mass and energy balances calculated show that the total air ratio of all test runs performed ranged between 1.39 and 1.47 and the average false air input amounted to approx. 10.1% (related to the total combustion air input, standard deviation: 4.1%). The amounts of false air have been considered in the subsequent evaluations of the test runs.

### 3.3 Results derived from the test runs regarding $NO_x$ emissions

Figure 2 and Figure 3 show the influence of the air ratio in the PCC, the residence time in the PCC, and the type of flue gas recirculation on $NO_x$ emissions for full load operation.

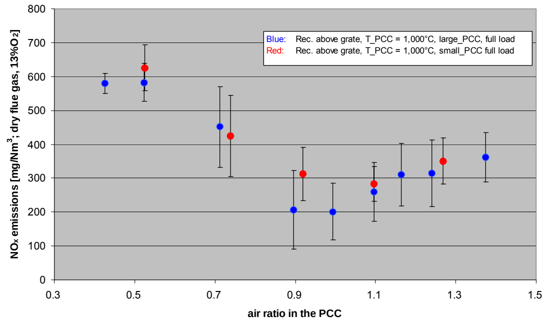


**Figure 2:** **A**ir ratio in the PCC versus $NO_x$ emissions for varying residence time

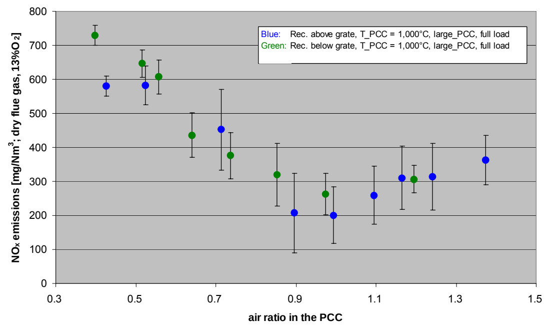


**Figure 3:** Air ratio in the PCC versus $NO_x$ emissions for varying type of flue gas recirculation

The results show that the air ratio in the PCC has a strong influence on $NO_x$ emissions. An optimum can be observed at an air ratio in the PCC between 0.9 and 1.0, where the $NO_x$ emissions amount to approx. 200 mg/Nm³ (dry flue gas, 13%$O_2$) (for a temperature in the PCC of 1,000°C, recirculation below the grate and high residence time (large PCC)). The highest $NO_x$ emissions have been observed at air ratios in the PCC between 0.4 and 0.5 with $NO_x$ emissions between 580 and 730mg/Nm³ (dry flue gas, 13%$O_2$).

Former studies [3, 4, 5, 6, 7] show an optimum air ratio in the PCC between 0.6 and 0.9. The difference regarding the optimum is probably caused by the fact that false air in the PCC was not taken into consideration in these studies. During the test runs performed false air, especially in the PCC has been minimized which was not the case in the other studies. This also stresses the importance of considering and minimizing false air input as false air cannot be controlled and may lead to wrong set-point values for an optimized air staging.

Figure 2 also indicates that the residence time in the PCC (volume of the PCC) has an influence on $NO_x$ emissions. $NO_x$ emissions increase with decreasing residence time. The estimated residence time in the PCC for the test runs performed varies between 1 and 2 seconds for the long PCC and between 0.6 and 1.3 seconds for the small PCC depending on the air ratio in the PCC applied. This effect seems to be smaller than the effect of the air ratio in the PCC but this influence may become more important at small residence time (<0.5s). Previous studies performed also indicate an influence of the residence time in the PCC on $NO_x$ emissions [3, 4, 5].

Furthermore, the type of flue gas recirculation seems to have an effect on $NO_x$ emissions. Flue gas recirculation above the grate seems to be slightly more efficient regarding $NO_x$ reduction than flue gas recirculation below the grate (see Figure 3). This may be due to the fact that flue gas recirculation above the grate improves the mixing and may also increase the mean residence time in the PCC.

Figure 4 shows the influence of the load on $NO_x$ emissions. The results show that $NO_x$ emissions at partial load are lower than at full load which again may be due to longer available residence times at partial load. In addition, a slight shift of the minimum regarding $NO_x$ emissions to higher air ratios in the PCC can be observed at partial load.

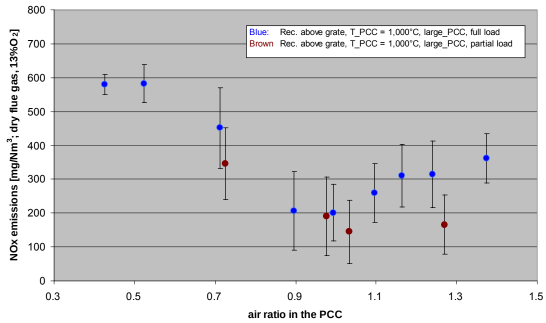


**Figure 4:** Air ratio in the PCC versus $NO_x$ emissions for varying load conditions

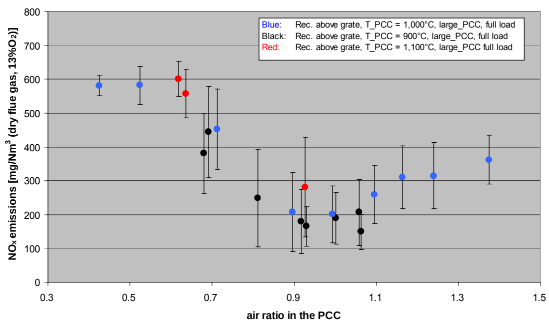


**Figure 5:** Air ratio in the PCC versus $NO_x$ emissions for varying temperatures in the PCC

Moreover, $NO_x$ emissions are influenced by the temperature in the PCC which is illustrated in Figure 5. The lowest $NO_x$ emissions were measured at temperatures of 900°C at an air ratio in the PCC of 1.06. This shows that $NO_x$ emissions decrease with decreasing temperature in the PCC. Former studies presented an optimum of the temperature in the PCC between 1,000 and 1,200°C [3, 4, 5]. But these temperatures where measured at the inlet [3, 4] or in the middle [5] and not at the end of the PCC. Therefore, these results are not directly comparable with the results of these studies. Typically there is no even temperature distribution in the PCC, especially not in the area above the grate. Therefore, in this study a location for the temperature measurement was chosen where the temperature in the flue gas starts to equalize (temperature in the second duct of the PCC). The influence was therefore only studied for long residence times in the PCC (large PCC).

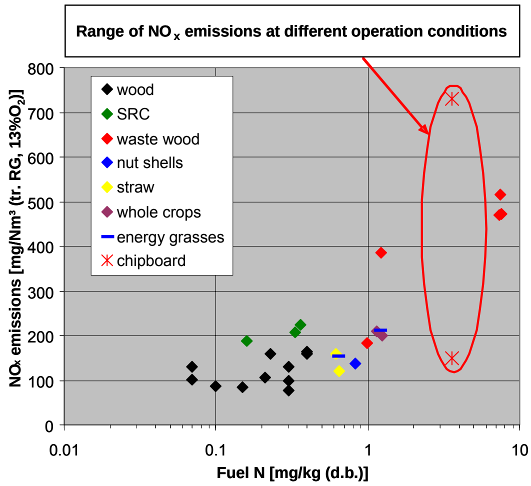


**Figure 6:** $NO_x$ reduction potential of chipboard compared with $NO_x$ emissions of other biomass fuels

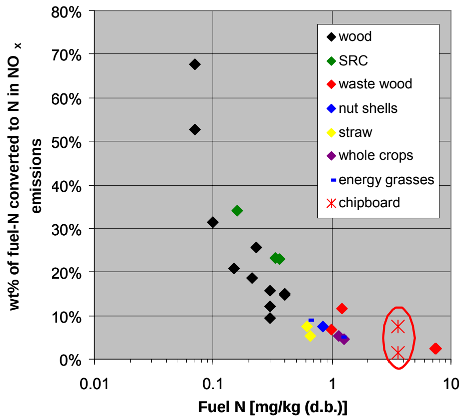


**Figure 7:** Conversion of the fuel-N into $NO_x$ emissions for chipboard compared with other biomass fuels

Figure 6 shows the $NO_x$ reduction potential by applying an efficient and advanced air staging concept. The $NO_x$ emissions of chipboard are compared with typical $NO_x$ emissions from other biomass fuels (applied in modern grate combustion plants with air staging). $NO_x$ emissions are normally increasing with the N content of the fuel. Consequently, an efficient air staging concept has rising importance for biomass fuels with high N content. Figure 6 also shows the wide variation of $NO_x$ emissions measured during the test runs performed and demonstrates that low $NO_x$ emissions are also achievable for fuels with high N content by an efficient application of primary measures.

Figure 7 shows that depending on the operational conditions between 1.5 % and 7.4 % of the fuel-N is converted into N in $NO_x$ emissions. Figure 7 also shows that N conversion depends on the N content of the fuel. The conversion of the fuel-N into N in $NO_x$ increases with decreasing N content. However, although the conversion rate of the fuel-N is lower for fuels with high N content, the total $NO_x$ emissions are higher (comparison of Figure 6 with Figure 7).

### 3.3 Results derived from the test runs regarding $PM_1$ emissions

$PM_1$ emissions decrease with increasing volume flow through the fuel bed (see Figure 8). This effect seems to be due to lower fuel bed temperatures at higher air flows which is confirmed by results of CFD calculations performed.

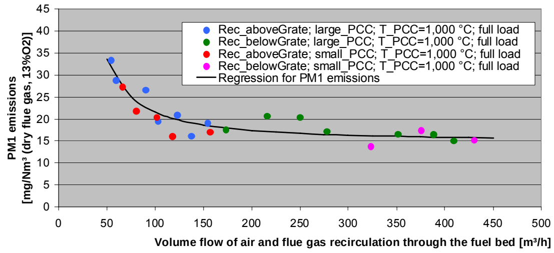


**Figure 8:** $PM_1$ emissions versus volume flow of air and flue gas recirculation through the fuel bed

Explanations: correlation calculated is statistically highly significant

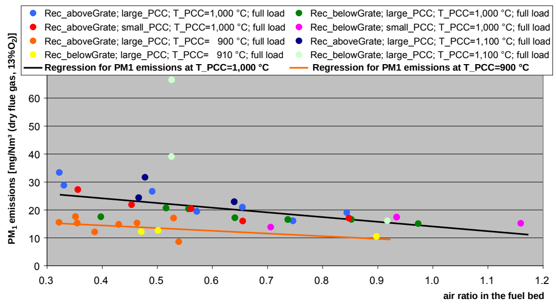


**Figure 9:** $PM_1$ emissions versus air ratio in the fuel bed and temperature in the PCC

Explanations: both correlations calculated are statistically significant

In addition, the temperature in the PCC shows an influence on $PM_1$ emissions (see Figure 9). At high temperatures $PM_1$ emissions increase. This can be explained by the fact that the flue gas temperature in the PCC influences the radiation on the fuel bed and thus its temperature. The influence seems to be more pronounced for low air ratios (low volume flow through the bed).

## 4. CONCLUSIONS & OUTLOOK

Test runs as a basis for the development of low emission biomass combustion systems by applying advanced air staging have been carried out at a 150kW pilot-scale grate combustion plant for chipboard (a N-rich biomass fuel). The results of the test series showed that

$NO_x$ emissions are mainly influenced by the air ratio in the PCC. An optimum can be observed at an air ratio between 0.9 and 1.0. In this respect it should be stated that false air flows in the PCC should be avoided as good as possible because they cannot be controlled. This means that the leakage of air in the combustion plant should be minimized which makes almost air tight fuel feeding and ash discharge systems necessary.

A second relevant influencing parameter indentified is the residence time in the PCC. Increasing residence time decreases $NO_x$ emissions. This is also confirmed by test runs performed at partial load. This influencing parameter is the more important the smaller the residence time is. As a guiding value a residence time of equal or larger than 1.0 second can be mentioned.

Additional influencing parameters identified but of less relevance are the temperature in the PCC and the type of flue gas recirculation. According to the test run results, a temperature of 900 – 1,000 °C in the PCC should be kept (to be controlled by flue gas recirculation) and flue gas recirculation should be preferably applied above the grate as by this measure the mixing of the gases can be improved.

Regarding $PM_1$ emissions, two relevant influencing parameters could be identified by the air staging tests. One relevant influencing parameter is the volume flow of the gas through the fuel bed (sum of primary air and flue gas recirculation below the grate). A statistically highly significant correlation could be identified that with rising gas flow through the fuel bed $PM_1$ emissions decrease. This is due to the fact that the gas flow causes a cooling effect as not the whole oxygen supplied is consumed in the bed which is confirmed by CFD simulations of packed biomass fuel beds [8]. The effect gets the more pronounced the lower the gas flow is.

A second relevant influencing parameter is the temperature in the PCC. As higher gas temperatures cause higher radiation, they also influence the bed temperature. This effect gets the more pronounced the lower the gas flow through the grate is.

Concluding, a moderate temperature in the PCC (around 900 °C), long enough residence time (guiding value 1.0 s), keeping the air ratio around 1.0 and applying a reasonable volume flow through the fuel bed (combination of flue gas recirculation above and below the grate) can fulfill all relevant requirements for low $NO_x$ as well as low $PM_1$ emissions. Regarding the implementation of this air staging method, an appropriate process control is necessary which ensures the keeping of the required parameters at varying load and varying fuel qualities.

Future work foresees similar air staging tests with other biomass fuels in order to evaluate whether the findings for chipboard are also applicable for a broader fuel spectrum.

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## 6 ACKNOWLEDGEMENTS

We gratefully acknowledge the COMET-programme of the Austrian federal government for funding the work presented in this paper.