Emission reduction process for the energetic use of biogenic residues

Mario König*, Mirjam Müller, Ingo Hartmann

DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH
Torgauer Str. 116, 04347 Leipzig

*E-mail: mario.koenig@dbfz.de

Abstract. During the combustion of biogenic residues particulate matter, nitrogen oxides, chlorine and sulphur compounds as well as dioxins and furans occur in elevated concentrations depending on the respective fuel composition. Corresponding abatement technology is only available for the power plant sector and cannot be used economically on small biomass plants. Therefore an exhaust gas purification procedure was developed and tested which can be used economically in decentral biomass plants. The core of the exhaust aftertreatment process is a fabric filter with catalytically active filter bags which enables a combined reduction of dust and nitrogen oxides. An additional precoating of the fabric filter also removes acidic exhaust gas components such as SO₂ and HCl. Experiments were conducted on pilot and field scale. Significant reduction of particle emissions, nitrogen oxides and chlorine compounds could be achieved. Further optimization of the quantities of reducing agent and precoat material supplied is necessary in order to improve the performance of the exhaust gas cleaning process.

1. Introduction

The transformation from a fossil-based to a bio-based economy is evolving worldwide. This is associated with an increased use of wood assortments and agricultural plants for material purposes. Therefore, a further expansion of energetic biomass use is only possible based on biogenic residues and waste materials. In comparison to wood fuels biogenic residues and wastes contain elevated concentrations of emission forming elements leading to high emissions of particulate matter (PM), nitrogen oxides (NOₓ), chlorine (HCl) and sulphur compounds (SO₂) during combustion. Corresponding abatement technology is only available for the power plant sector and cannot be used economically on small biomass plants. The aim of the presented work is to demonstrate an exhaust gas purification procedure which can be used economically in decentral biomass plants. The core of the exhaust aftertreatment process is a fabric filter with catalytically active filter bags which enables a combined reduction of dust and nitrogen oxides. An additional precoating (calcium hydroxide) of the fabric filter also removes acidic exhaust gas components such as SO₂ and HCl from the exhaust gas.

2. Framework conditions for the energetic use of biogenic residues

When developing an exhaust gas purification system for biogenic residues, legal, technical and economic framework conditions must be taken into account from the beginning. Only in this way the process can be used in practice in the future and provide a contribution to an increased environmentally friendly use of biogenic residues.

2.1. Legal framework

The production of energy from biomass is subject to various national and European regulations. There are a number of fuel- and plant related legal regulations that must be observed, especially for biogenic residual materials. Only the regulations concerning airborne pollutant emissions from the combustion of solid biofuels will be presented here, because they are of particular relevance for the presented results. In addition, when using biogenic residues for energy purposes, the respective national regulations regarding the approval and operation of the plants must always be taken into account.
comprehensive overview and an evaluation of the legal requirements for the energetic use of biomass is given using the example of Germany.

In the European Union the most important acts for biomass combustion plants are the Eco design Directive 2009/125/EC [2] with the associated Commission Regulations 2015/1185 [3] and 2015/1189 [4] and the Directive 2015/2193/EU [5] on the limitation of emissions from medium combustion plants. To date the Eco design Directive only regulates combustion plants for woody biomass below a nominal heat output of 500 kW. For non-woody biomass, only for combustion plants with a rated thermal output of more than 1 MW emission limit values have been set so far. Table 1 shows the limits for solid biofuels in Europe for plants between 1 and 50 MW thermal output.

**Table 1.** European emissions limits for solid biofuels in medium sized plants [5]

| Plant type | Output MW | NO$_X$ | SO$_2$ | PM |
|------------|-----------|--------|--------|----|
| Existing   | 1 - 5     | 650    | 200    | 50 |
| Plants     | 5 - 50    | 650    | 200    | 30 |
| New        | 1 - 5     | 500    | 200    | 50 |
| Plants     | 5 - 50    | 300    | 200    | 20 |

The requirements laid down in Directive 2193 have to be understood as minimum requirements and the member states of the EU have to transpose these requirements into national law, whereby they can set stricter limit values and also for additional pollutants. Table 2 shows as an example the German emission limits for solid biofuels. The limits of the 44. BImSchV [6] are a result of an amendment of the former TA Luft [7] under consideration of the European legal requirements of the Directive 2193.

**Table 2.** German emission limits for solid biofuels in new plants [6]

| Output MW | CO | VOC | NO$_X$ | SO$_2$ | HCl | NH$_3$ | PM |
|-----------|----|-----|--------|--------|-----|--------|----|
| 0.1 - 1   | 370| 50  | 750    | 200    | 45  | 30     | 20*|
| 1 - 5     | 220| 10  | 370    | 200    | 45  | 30     | 20 |
| 5 - 15    | 220| 10  | 300    | 200    | 45  | 30     | 20 |
| 15 - 20   | 220| 10  | 200    | 200    | 45  | 30     | 10 |
| 20 - 50   | 220| 10  | 200    | 100    | 45  | 30     | 10 |

* For existing plants 30, for non-woody fuels in new plants 30 mg/m$^3$ STP 6 vol% O$_2$

Table 2 shows exclusively the emission limits for new installed plants but there exist many exemptions for existing plants and for special fuels which can be found in [6].

2.2. **Technical framework**

A prerequisite for the utilisation of biogenic residues as fuel is the use of suitable combustion technology, which above all masters the relatively high ash contents and low ash melting temperatures. The plants need to be equipped with an ash moving element (moving grate, ash slider or vibration grate) in order to remove the ash constantly from the combustion chamber and prevent ash agglomeration. Another way to prevent ash slagging is to cool the grate with water. Applying this combustion technology a good burnout can be achieved with low CO and VOC emissions.

Other relevant groups of pollutants like particulate matter, nitrogen oxides, sulphur and chlorine compounds are mainly produced from the fuel-bound components and can only be influenced to a limited extent by primary emissions reduction measures. For example, NO$_X$ emissions depend directly
on the nitrogen content in the biomass fuel since prompt and thermal NO is hardly produced during biomass combustion due to insufficient temperatures [8]. About two thirds of the nitrogen bound in the fuel is oxidized to NO, the remaining nitrogen is converted into N₂ [9]. Similar correlations were found for the content of chlorine in the fuel and chlorinated pollutants like HCl, PCDD/F, PCBz and PCPh [10], the content of sulphur and sulphurous emissions and the content of particle forming elements like K, Na, S, Cl and the particle emissions [11]. Therefore secondary abatement technology has to be utilized to achieve a substantial reduction of PM, NOₓ, HCl and SO₂- emissions from the combustion of non-woody solid biomass.

Technology for secondary emission control of these pollutants is state of the art in power and incineration plants. Table 3 gives an overview about the relevant exhaust gas purification methods.

### Table 3. Established emission reduction measures for large-scale plants [8].

| Pollutant | Method   | Process equipment                      | Limitations            | Reduction |
|-----------|----------|----------------------------------------|------------------------|-----------|
| PM        | Inertial separation | Cyclones, Multicyclones | Particles < 3 μm | 30 - 65 %  |
|           | Filtration | Fabric filter, depth filters | Temp. > 300 °C | 99 %      |
|           | Electrostatics | Electrostatic precipitator | Only wood fuels | 95 %      |
| NOₓ       | SNCR      | Dosing system, reducing agent | High NH₃-slip | 50 %      |
|           | SCR       | SCR-Catalyst (Monoliths) | Temp. < 250 °C | up to 95 % |
| HCl       | Sorption  | Adsorber, Washer | Temp. > 220 °C | up to 90 % |
| SO₂       | Sorption  | Adsorber, Washer | Temp. > 220 °C | up to 90 % |

As electrostatic precipitators only achieve high precipitation rates for wood fuels, the particle separation in the combustion of non-woody biofuels has to be realized with a filtration process. The filter bags usually cannot resist temperatures above 300 °C in the long term. Moreover they have to be protected from sparks in order to prevent burning. Therefore a cyclone is often used as pre-separator.

Selective non-catalytic reduction (SNCR) of NOₓ is often applied in incineration plants. But this method is only working in a narrow temperature window which is difficult to realize in smaller plants. The standard catalyst for the power plant sector is a V₂O₅-WO₃ on TiO₂ and has his optimum activity in a temperature window between 260 to 425 °C [12]. For efficiency reasons these temperatures are much too high for biomass plants so that low-temperature SCR catalyst has to be applied which are active at temperatures below 200 °C. In recent years, numerous research projects have been carried out on the subject of low-temperature SCR and promising materials for low-temperature denitrification have been found [13]. In order to reduce the nitrogen compounds to N₂ a reducing agent has to be injected into the gas stream. For stationary applications the most widely used and best researched reaction mechanism is NH₃-SCR. As reducing agent different ammonia-sources can be applied e.g. anhydrous ammonia, liquefied ammonia, ammonium carbamate or urea solution [14]. Pure ammonia and ammonia water are hazardous materials and there are high requirements on handling and storage. A much more saver alternative is urea solution ((NH₂)$_2$CO) which is applied for cleaning the exhaust gas of diesel engines. The European standard ISO 22241 defines the properties of the reducing agent AUS32 (AdBlue) [15]. AdBlue seems to be a suitable ammonia-source for application in decentral biomass plants since it is a standardized product which is easily available, transportable and storable. A main problem of using urea for low-temperature SCR is that the conversion of urea to NH₃ does not take place completely below 200 °C [16].

Reduction of acidic gaseous compounds like HCl and SO₂ is realized with washers or adsorbers. Dry adsorption processes are preferred for entrained flow adsorption because, in comparison to adsorption, no waste water is produced which has to be reprocessed or disposed of. The sorbent (e.g. lime hydrate, sodium hydrogen carbonate) is added to the exhaust gas where it reacts with the chlorine and sulphur and the solid reaction products can be separated with a filter. For dry sorption temperatures of 220 °C should not be exceeded since desorption can take place at higher temperatures [8].
2.3. Economic framework
Considering the technical requirements of biogenic residues it can be stated that the investment costs for a combustion plant which is able to handle different biofuels are higher than that of a conventional plant for wood or fossil fuels. Therefore economic operation can only be achieved from a certain plant size onwards. On the other hand there is the economic necessity of short transport distances, since the energy density of biogenic residues is usually relatively low and high transport and storage costs has to be avoid. This means the plants must not be too small to reach the scale of economy, but nevertheless must be constructed and operated decentrally in order to avoid economic and ecological disadvantages.

The high amounts of particulate matter from residues has to be controlled with a fabric filter since the separation efficiency of cyclones and ESP is too low. Fabric filters have high operation costs, but within the power range between 0.1 and 1 MW they show 15 - 20 % lower investment costs compared to ESP [17]. Up to now, for plants up to 1 MW heat output mainly electrostatic precipitators are available. In a market overview from the year 2017, 18 ESP and only three fabric filters were listed for that power range [18].

The Selective Catalytic Reduction of NOx shows five times the cost of Selective Non-Catalytic Reduction. But one main argument for the SCR-technology beside the higher possible conversion rates is the low NH3-slip which is relevant for the limit value. As mentioned above, for economic reasons lower temperatures must be achieved with the SCR catalysts. Another important aspect is, that the SCR catalysts are usually applied as a separate module in the form of monoliths and therefore cause high operating and investment costs. In biomass combustion appliances a combination of particle filtration and SCR can save space, material and energy. First studies on the combined NOx and PM capture with a fabric filter were conducted in [19] and [20] achieving a NO conversion up to 90 %. Another approach is the impregnation of filter candles based on SiC with a catalyst system based on TiO2–V2O5–WO3. In a pilot test an average NO conversion of 83.3 % was achieved and additionally SO2 could be removed [21]. Probably the depth filtration approach was not further pursued for cost reasons.

In order to achieve an economic operation of combustion plants for biogenic residues and wastes cost advantages compared to conventional exhaust gas cleaning technology have to be achieved through space savings, energy savings, the use of components from the automotive industry and a modular design.

3. Material and methods

3.1. Structure and components of the emission reduction process
Based on the framework conditions described in section 2 a method was developed for exhaust gas cleaning of decentral combustion of non-woody solid biofuels. The process scheme in figure 1 shows the principle approach of the cleaning system.

Core element is a fabric filter with catalytically active filter bags. The reducing agent AdBlue is injected directly into the heat exchanger of the boiler in order to ensure that the urea is completely transformed to ammonia. The injection of the urea solution is realized with a two-fluid nozzle using compressed air to achieve a fine atomization and to cool and flush the tip of the nozzle to prevent blocking. A cyclone is arranged upstream of the filter for the separation of coarse particles and to protect the filter bags from sparks. After the cyclone a precoat material is fed into the exhaust gas in order to adsorb acidic gaseous compounds. On the outside of the filter bags the particulate matter and the precoat material is deposited forming a filter cake. Together with the reducing agent, the dust-free exhaust gas passes through the outer bag and reaches the catalytically coated inner bag where the NH3-SCR takes place. The deposition of the dust and precoat material upstream of the catalyst protects it from blockage and deactivation. Moreover the filter cake increases the precipitation efficiency for PM and acidic gaseous compounds. In order to ensure a sufficient DeNOx efficiency with a low ammonia slip, the current nitrogen oxide concentration in the clean gas are observed continuously with a NOx probe from the automotive industry. That allows an automatic adjustment of the quantity of reducing agent in order to be able to operate the NH3-SCR always at the optimum level.
3.2. Fuels and experimental plants

Different non-woody biofuels were used in the experiments on two different combustion plants. Table 4 shows the results of the fuel analysis. The fuels show a similar level regarding the heating value and the content of C and H. Significant differences can be found between straw and miscanthus regarding the ash content and the elemental composition. Miscanthus contains less N, S, Cl and K which means that lower emissions of PM, NO\textsubscript{X}, SO\textsubscript{2} and HCl can be expected during combustion.

| Fuel          | LHV  | H\textsubscript{2}O | Ash | C   | H   | N   | S   | Cl  | K   | Na  | Si  |
|---------------|------|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|               | MJ/kg| w%                  | w\%\text{dry} | w\%\text{dry} | w\%\text{dry} | w\%\text{dry} | mg/kg\text{dry} | mg/kg\text{dry} | mg/kg\text{dry} | mg/kg\text{dry} | mg/kg\text{dry} |
| Wheat straw 1 | 16.7 | 8.8                 | 7.3 | 45.1| 5.1 | 0.61| 0.10| 0.28| 14,500 | 161 | 17,800 |
| Wheat straw 2 | 17.7 | 10.5                | 6.2 | 46.4| 5.9 | 0.83| 0.16| 0.36| 9,460  | 529 | 14,400 |
| Miscanthus    | 17.5 | 11.6                | 1.9 | 48.3| n.a.| 0.30| 0.05| 0.03| 1,900  | 11.5 | 4,300  |

Pellets with a standardized diameter of 6 mm were produced from wheat straw 1 and 2 and used in experiments on a 100 kW pilot-scale boiler with a moving grate. For feeding of the reducing agent a two-stream nozzle with a nozzle diameter of 0.3 mm was mounted directly in front of the boiler at the second deflection of the heat exchanger ducts. The temperature at this position is more than 300 °C which is enough in order to disintegrate completely the urea solution in NH\textsubscript{3} and HNCO by thermolysis. Exact dosing of very low amounts of urea solution was realized with a MFC (liquiflow) from the company Bronkhorst. The precoat material lime hydrate (Ca(OH)\textsubscript{2}) was feded directly after the cyclone into the exhaust gas with a spiral dosing unit. The filter is equipped with 16 PTFE filter bags and catalytically coated inner bags. The catalyst coating is based on TiO\textsubscript{2}, V\textsubscript{2}O\textsubscript{3} and WO\textsubscript{3} [22].

The chopped miscanthus was used in a field plant which was operated at an average heat output of 300 kW. The conversion plant has a water cooled combustion chamber, an ash slider and an automatic ash removal to ensure continuously operation with non-woody biofuels. The plant was equipped with appropriate cyclone, precoat-dosing and a filter with 72 catalytically active filter bags similar to those in the pilot plant. Similar to the pilot plant the reducing agent for SCR was injected into a redirection of the heat exchanger where temperatures over 300 °C prevail. For dosing a laboratory peristaltic pump from the producer Medorex was used which allows dosing rates between 0.55 and 55.0 ml/min. However, preliminary tests have shown that continuous dosing with the pump is only possible at volume flows above 10 ml/min.
3.3. Experiments and measurement methods
Experiments on the pilot and the field plant were conducted in order to determine the performance of the gas cleaning process. In preliminary tests, optimal boiler settings with the different biofuels were found to achieve stable low-emission combustion. With the found settings combustion experiments were carried out in order to determine raw gas and clean gas emissions depending on the quantities of reducing agent (AdBlue) and precoat material (lime hydrate Ca(OH)₂) supplied. During the ignition phase, the filter was bypassed until the temperature of the exhaust gas and on the filter reached 100 °C to prevent condensation and sticking. The filter was operated in a pressure drop range of 5 to 20 mbar which are standard operating conditions for bag filters [8].

The operating status of the system was continuously monitored by numerous sensors (temperature, pressure). For determination of the exhaust gas composition, the following measurement techniques were applied:
- Fourier-transform infrared spectrometer (FTIR, manufacturer Calemex)
- Paramagnetic oxygen analyzer (manufacturer M&C, type PMA 100)
- Particle measuring system (manufacturer Paul Gothe)

The concentration of the gaseous emissions was continuously measured using Fourier-transform infrared spectroscopy. A paramagnetic oxygen analyzer was used to measure the oxygen content of the exhaust gas. The total particulate matter concentration in the flue gas was determined according to the VDI 2066/1 with gravimetric measurement. All measured emissions were converted to standard conditions (STP 0 °C, 101,325 Pa) and referred to 6 % oxygen. The NOₓ concentration was calculated as NO₂-equivalent from the measured NO and NO₂ values. Acidic gases were measured as SO₂ and HCl.

4. Results and discussion
The results of the reference tests without emission reduction measures are presented in Table 5. All numbers are an average over three 15-min average values in stable operating phases.

| Fuel          | Heat output kW | H₂O vol% | O₂ vol% | CO mg/m³ (STP, referred to 6 vol% O₂) | NOₓ mg/m³ | SO₂ mg/m³ | HCl mg/m³ | PM mg/m³ |
|---------------|----------------|----------|---------|--------------------------------------|------------|------------|------------|----------|
| Wheat straw 1 | 100            | 8.6      | 13.7    | 271                                  | 733        | 179        | 23         | 339      |
| Wheat straw 2 | 100            | 7.8      | 12.4    | 213                                  | 702        | 294        | 232        | 524      |
| Miscanthus     | 300            | 8.0      | 10.1    | 50                                   | 513        | 107        | 8          | 153      |

For all fuels a sufficient burnout was achieved with a low concentration of incompletely oxidized exhaust gas components, which is proven by the relatively low CO emissions. The wheat straw 2 pellets showed a higher PM-value than the wheat straw 1 pellets or the miscanthus fuel which can be attributed to a higher amount of particle forming elements. Although wheat straw 1 contains more potassium than wheat straw 2 the sum of particle forming elements (S, Cl, K, Na) is higher for wheat straw 2 leading to higher PM emissions. Moreover wheat straw 1 contains more Si which is able to bound K into the ash and thereby reduces PM [23].

The NOₓ emissions are relatively high for the straw pellets above the legal limit for medium-sized plants with more than 1 MW heat output. The mixed pellets and miscanthus comply with the European minimum requirements for existing plants but exceed the NOₓ limit values for new plants. The SO₂ limit of 200 mg/m³ (STP 6 vol% O₂) is only exceeded by the straw 2 pellets. The HCl limit of 45 mg/m³ (STP 6 vol% O₂) is significantly exceeded by the straw 2 pellets. The strong deviation of the HCl values of straw 1 and straw 2 cannot be explained by different chlorine contents in the fuel, as these differ only slightly. Probably leaching effects of chlorine by water (rain) play a role here or there was a technical measure problem. Higher HCl emissions were expected for straw 1 on the basis of the fuel analysis.
The precipitation efficiency of the fabric filter was determined in both plants by measuring the PM concentration in bypass and filter operation. Figure 2 shows the results of the dust measurements on the pilot and field plant. For the straw fuels a precipitation efficiency of 87.3% and 90.5% was achieved on the pilot plant. The filter on the field plant achieved an average precipitation efficiency of 94.1%. The lower efficiencies on the pilot plant can be explained by higher raw gas emissions of the straw fuels and in addition with a detected leak at the bypass of the pilot plant. Before the measurements with straw 2, the leakage was eliminated by installing new bypass valves that close more tightly. Furthermore, a new sealing was inserted into the filter head plate. However, only a slight increase in separation efficiency was achieved by this measure, so that it cannot be excluded that further leaks could lead to a reduced precipitation efficiency.

For all fuels a PM concentration in the clean gas below 50 mg/m³ (STP, 6 vol% O₂) has been reached, whereby the European requirements up to a plant size of 5 MW are met. With the straw pellets the German requirements are only met for existing plants. With the filter on the field plant all legal requirements could be met for the fuel Miscanthus. Also the effect of precoating was investigated finding a slightly increase of precipitation efficiency in the experiments on the field plant. Figure 2 shows on the right side the precipitation efficiency of the dust filter without precoat material and with an addition of 50, 100 and 150 grams per hour of precoat material into the exhaust gas system upstream of the filter. The precoat material accumulates on the filter surface and forms a filter cake together with the dust particles. Thus the precipitation efficiency could be increased by up to 2%.

Reduction of nitrogen oxides was achieved when feeding urea solution in the heat exchanger of the boiler. The achieved NOₓ-reduction was higher in the pilot plant than in the field plant because it was very difficult to achieve temperatures over 150 °C under practical conditions. The achieved DeNOₓ efficiency strongly depends on the temperature and the available NH₃ on the catalytic filter. Figure 3 shows the average DeNOₓ efficiency for all tested fuels. In average it was achieved a NOₓ reduction of 58.8% for straw 1, 48.9% for straw 2 and 43.9% for miscanthus on the 300 kW boiler. On the right side of figure 3 the NOₓ conversion and corresponding NH₃-slip depending on the added amount of urea solution is shown for the fuel straw 2 at a filter temperature of 200 °C. When increasing the added amount of urea at constant temperatures the DeNOₓ efficiency but also the NH₃-slip increases. Above a certain amount of urea injection, the conversion rate no longer increases but only the unwanted NH₃-slip.
The low efficiency on the field plant is due to maximum temperature on the filter of 155 °C. When achieving higher temperatures the DeNO$_X$ efficiency increases rapidly at constant feeding rates as it can be seen in figure 4. On the pilot plant a maximum DeNO$_X$ efficiency of 61 % was achieved with straw 2 at a feeding rate of 150 g/h and a filter temperature of 207 °C. On the field plant with the fuel miscanthus it was observed a slow increase in NO$_X$ conversion and a sudden increase in NH$_3$ slip. This shows that the temperatures of max. 155 °C at the catalyst are not sufficient to convert most of the NH$_3$ present at the catalyst. However, it can also be seen that if the amount of reducing agent added remains constant from a temperature of 150 °C onwards, the NH$_3$ slip decreases while the NO$_X$ conversion increases. Accordingly, a higher NO$_X$ conversion is to be expected with rising temperatures at the field plant.

Beside NO$_X$ and PM also the acidic gaseous components SO$_2$ and HCl were observed in order to determine abatement efficiencies dependend on the added amount of precoat material (see Table 6). One interesting fact observed in the experiments with urea solution was, that the HCl concentration decreased significantly when injecting AdBlue. This is probably due to a reaction of ammonia and HCl to form the ammonium chloride salt. Additionally an influence on SO$_2$ emissions was observed when switching from bypass to filter operation. Without any precoating the SO$_2$ drops down significantly about 60-80 %.
This can be explained by the initially low temperatures at the filter, as sulphate compounds are formed at lower temperatures which precipitate as salts and can deposit on the filter. With increasing temperatures on the filter an increase of the SO\textsubscript{2}-concentration in the exhaust gas was observed.

Table 6. Emission values depending on precoat and reducing agent amounts

| Fuel Plant               | Ca(OH)\textsubscript{2} g/h | AdBlue g/h | NO\textsubscript{x} | NH\textsubscript{3} mg/m\textsuperscript{3} (STP, referred to 6 vol\% O\textsubscript{2}) | SO\textsubscript{2} | HCl | PM |
|-------------------------|-------------------------------|-------------|---------------------|--------------------------------------------------------------------------------|----------------|-----|-----|
| Wheat straw 2 100 kW    | 105                           | 0           | 717                 | 1                                                                               | 272            | 197 | 81  |
|                         | 210                           | 0           | 717                 | 3                                                                               | 264            | 109 | 92  |
| pilot plant             | 210                           | 150         | 477                 | 12                                                                              | 256            | 50  | n.a.|
|                         | 0                             | 150         | 372                 | 11                                                                              | 289            | 112 | n.a.|
| Miscanthus 300 kW       | 50                            | 0           | 343                 | 0                                                                               | 100            | 4.4 | 8.3 |
| field plant             | 100                           | 0           | 350                 | 0                                                                               | 103            | 4.6 | 5.6 |
|                         | 150                           | 0           | 358                 | 0                                                                               | 103            | 4.7 | 5.4 |
|                         | 0                             | 450         | 278                 | 112                                                                             | 165            | 1.3 | 9.1 |

Precoating on the pilot plant showed no significant reduction of SO\textsubscript{2} and PM. The only effect observed was a reduction of HCl about 53 %. When combining precoat and urea NO\textsubscript{x} could be reduced about 32 % and HCl even about 78 %. When feeding only urea the NO\textsubscript{x}-reduction increased to 47 % and still HCl was reduced about 52 % in comparison to the reference value.

On the field plant feeding of precoat material supported the precipitation of particles and HCl starting from an already low level. The sole supply of urea solution decreased the NO\textsubscript{x}-emissions about 46 % and HCl about 84 %. No reduction of SO\textsubscript{2} caused by the precoate material was observed.

5. Conclusions

The emission reduction method was investigated on a pilot and a practical scale. The experiments on the pilot plant showed that the combustion of straw not only leads to high emissions of particulate matter but also cause relevant concentrations of gaseous pollutants like NO\textsubscript{x}, SO\textsubscript{2} and HCl which in various cases lead to national or European limit values being exceeded. It was investigated the potential of the method for reduction of these pollutants. For NO\textsubscript{x} it was found a sufficient conversion rate of more than 50 % at exhaust gas temperatures above 200 °C. Another effect of the injection of AdBlue into the heat exchanger was a significant reduction of HCl. In contrast, the precoating of the filter on the pilot plant showed scarcely any effect on the SO\textsubscript{2} or PM values. Only the HCl value was reduced by half.

Regarding an appropriate amount of urea solution for achieve a sufficient NO\textsubscript{x}-conversion in straw combustion considering the emission limit for NH\textsubscript{3} of 30 mg/m\textsuperscript{3} (STP, 6 vol\% O\textsubscript{2}) it can be derived from the results a dosing quantity of 100 - 150 g/h for plants with an heat output of 100 kW. For larger systems or flue gas volume flows, the quantities must be adjusted accordingly. For fuels with a lower nitrogen content such as Miscanthus, the quantities of reducing agent introduced must be further reduced to ensure low ammonia slip.

The field experiments showed that in practice a major problem is, that sufficient temperatures on the SCR-catalyst are only reached after a longer period of operation and by modifications of the heat exchanger. In order to achieve higher conversion rates for NO\textsubscript{x} the temperatures at the catalyst have to be increased or new low-temperature catalysts has to be developed which are active below 150 °C.

Precoating of the filter decreased the particle emissions and the HCl-values. But as the values of PM and HCl already was on a very low level without precoating of the filter it is not clear if the same reduction efficiency can be achieved starting at higher emission levels. Regarding SO\textsubscript{2} no effect was observed caused by the precoate material.

In summary, it can be stated that the method investigated is well suited for the reduction of PM, NO\textsubscript{x} and HCl from boilers for non-woody biomass. Up to now, efficiency losses have to be tolerated, since...
the available SCR catalysts are only active at temperatures above 150 °C and an acceptable NOX conversion is only achieved at temperatures above 200 °C. This requires the development of suitable low-temperature SCR catalysts. With regard to sulfur-containing compounds, the precoating of the filter did not show sufficient effect. On the one hand, this can be related to problems with the precoat dosing unit, the distribution within the exhaust system and possible deposition of the material in the exhaust duct upstream of the filter due to too low flow velocities. On the other hand, the amount of supplied precoat material may have been insufficient, which will be investigated in more detail. With regard to HCl, it was shown that a sufficient reduction can already be achieved by the injection of urea solution. However, it must be considered in each individual case whether, depending on the HCl raw gas concentrations, compliance with the limit values can be achieved by only injecting reducing agent or by additional precoating.

For the fuel miscanthus it was shown that compliance with the limit values for the gaseous components NOX, SO2 and HCl can be achieved without secondary measures. When straw fuels are used, DeNOX and adsorptive gas cleaning may also be used in addition to a particle precipitator in order to comply with existing legal limit values.

References
[1] Antoni O, Probst C and Witschel C 2015 Legal requirements for the energetic use of biomass Würzburg studies on environmental energy law vol 4c Würzburg
[2] European Union 2009 Ecodesign directive 2009/125 Strasbourg
[3] European Union 2015 Commission regulation 1185 Brussels
[4] European Union 2015 Commission regulation 1189 Brussels
[5] European Union 2015 Directive (EU) 2015/2193 Strasbourg
[6] Federal Republic of Germany 2019 Regulation on medium-sized combustion, gas turbine and combustion engine plants - 44. BImSchV
[7] Federal Republic of Germany 2002 Technical instructions for keeping the air clean - TA Luft
[8] Kaltschmitt M and Hartmann H 2009 Energy from Biomass 2nd ed. Berlin: Springer
[9] Joos F 2006 Technical Combustion Berlin Heidelberg: Springer
[10] Launhardt T 2002 Environmental influences of the thermal use of solid biomass in small-scale plants Dissertation, Technical University of Munich
[11] Hartmann H, Roßmann P, Turowski P, Ellner-Schuberth F, Hopf N and Bimüller A 2007 Grains as fuel for small furnaces TFZ report 13 Straubing
[12] Mladenović M, Paprika M and Marinković A Renewable and Sustainable Energy Reviews 82 (2018) 3350–3364
[13] Fu M, Li C, Lu P, Qu L, Zhang M, Zhou Y, Yu M and Fang Y Catalysis Science Technology 4 (2014) 14–25
[14] Cheng X and Bi XT Particuology 16 (2014) 1–18
[15] ISO 22241-1:2006, Diesel engines -- NOx reduction agent AUS 32 -- Part 1: Quality requirements
[16] Bai H and Yu Lee T Environmental Science 3(2) (2016) 261–289
[17] Nussbaumer T 2006 State of the art and cost of fine dust separation in automatic wood combustion systems from 100 kW to 2 MW. Verenum: Zurich
[18] C.A.R.M.E.N. 2017 Supplier of particle precipitators for wood firing systems with focus on power range 100 KW to 1 MW Straubing
[19] Ness SR, Dunham GE, Weber GF and Ludlow DK Environmental Progress 14 (1995) 69–74
[20] Park YO, Lee KW and Rhee YW Journal of Industrial and Engineering Chemistry 15 (2009) 36–39
[21] Heidenreich S Nacken M Hackel M Schaub G Powder Technology 180 (2008) 86–90
[22] Pinke M Sassa R Mortimer W Brinckman G 1997 Catalytic Filter Material and Method of Making Same WO/1997/006877
[23] Hartmann I 2014 Solid bioenergy carriers Presentation on the FNR conference “Utilization of solid biofuels within the scope of the 1st BImSchV” Berlin