ABSTRACT: In the presented work, the combustion behaviour of straw pellets in small scale combustion systems is investigated, focusing on gaseous and particulate emissions. Three types of straw pellets, modified with additives, are fired in a 15 kW prototype residential heating boiler, and gaseous and particulate emissions are studied under varying operating conditions. Moreover, a novel heat exchanger technology – the Schräder Hydrocube® – is investigated focusing on the potential to reduce these emissions.

Particulate emissions could be reduced by 20 - 25% using the Hydrocube®, and the main separation effect of fine particles was identified to be due to the heat exchanger part of the system. Though reducing most particle fractions, a strong increase of the smallest fraction of 30 nm was measured. Applying the Hydrocube® system with an additional electronic charger, the separation efficiency was increased up to 65%. A significant reduction of HCl and SO\textsubscript{2} emissions could be observed in all experiments using the Hydrocube®. Elemental analyses showed low pH-values and an enrichment of several elements in the condensate from the heat exchanger system.

Keywords: combustion, emission reduction, straw

1 INTRODUCTION

In compliance with the Energy Policy of the European Union, Austria is aiming at increasing the share of renewables in domestic energy consumption. In order to meet the political targets, the utilisation of agricultural biomass, in addition to well established wooden biofuels, will be necessary in the field of heat production.

Among the variety of raw materials, straw has an outstanding position: As a residue from cereal production, cultivation and harvest technology are well established, and therefore cheaply utilised. Moreover, large amounts of this raw material are available in Austria, but also in several other European countries [1]-[3].

Despite these advantages, a number of problems and challenges have to be considered when firing straw, especially in small scale combustion units (< 400 kW). Together with unfavorable ash melting properties and the release of harmful or corrosive compounds, straw is known to release high dust emissions during combustion.

2 PURPOSE OF THE WORK

The presented work was conducted in the context of a project, investigating gaseous and particulate emissions but also corrosion effects on refractory materials, when firing straw pellets in small scale combustion units (cf. [4]). The objective of this work is the investigation of emissions from straw pellets combustion. Moreover, the potential to reduce these emissions by applying a specific heat exchanger with implemented flue gas cleaning technology will be studied and requirements and possibilities for further development of the investigated technology are discussed.

3 MATERIALS AND METHODS

3.1 Fuel

Previous work has shown that the ash melting properties of straw pellets can be enhanced by using Ca-, Mg-, but also Al-containing additives [5]-[8]. Several additives have been evaluated in preliminary experiments, focusing on ash melting behaviour and corrosive attack on refractory materials.

For the presented work, an aluminium containing additive and one with Ca- and Mg-carbonate were chosen. As a reference, pellets without additive were used as well. Table I gives an overview about the fuels and the additives used.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Additive</th>
<th>Share in pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel A</td>
<td>no additive</td>
<td>-</td>
</tr>
<tr>
<td>Fuel B</td>
<td>88 % Al\textsubscript{2}O\textsubscript{3}</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Fuel C</td>
<td>52 % CaCO\textsubscript{3}, 40 % MgCO\textsubscript{3}</td>
<td>3 %</td>
</tr>
</tbody>
</table>

3.2 Experimental setup

Straw-pellets are fired in a 15 kW prototype residential heating boiler, designed by KWB – Kraft und Wärme aus Biomasse. The flue gas from the boiler can either be led through the Schräder Hydrocube®, which is installed downstream the boiler, or be bypassed, going directly to the chimney. Figure 1 shows a schematic drawing of the experimental setup.
3.3 Measurements and analytical methods

During all tests, temperatures and volume flows of all water and condensate circuits have been measured in order to determine the heat supplied in each part of the system. In addition, the temperature in the combustion chamber as well as the temperature of the flue gas before entering the chimney and at several positions in the Hydrocube® have been determined (see also Figure 1).

CO₂, O₂, CO, NOₓ and SO₂ in the flue gas were analysed continuously during all experiments; HCl was determined via absorption in deionised water and detected by using ionic chromatography.

Particulate emissions were quantified gravimetrically according to VDI 2066 [9] using filter cartridges. Moreover, an ELPI (electronic low pressure impactor) was used to investigate the particle size distribution.

The elemental composition of the pellets, the flue gas condensate and the collected dust was analysed via ICP-OES after a microwave digestion.

3.4 Experimental program

Tests have been conducted with all three fuels under full load and part load (50% of nominal load) conditions, in order to investigate the performance of the Hydrocube® varying the velocity of the flue gas stream. Dust measurements have been performed at each operating point at standard conditions and using the Hydrocube®. In addition, some experiments have been conducted using the Hydrocube® technology equipped with an additional electronic charger and also using the Hydrocube® heat exchanger without operating the scrubber. The variations of the Hydrocube® application are shown in Figure 2 (a)-(d).

Figure 1: Experimental setup and measurement positions

In the Hydrocube® the flue gas is cooled down with a heat exchanger, followed by a scrubber that is operated with water and circulating condensate from the flue gas. The energy from the heat exchanger is used to warm up the cold flow from the heating circuit; the heat from the condensate is used to produce hot water for domestic use.

Figure 2: Variations of the experimental setup

Gaseous compounds in the flue gas as well as the elemental composition of fuels, dust emissions and condensates have been analysed, in order to determine the elemental distribution.

Table II gives an overview about the variations of the experimental program.
### 4 RESULTS

#### 4.1 Fuel properties

Table III shows the results from the fuel analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fuel A</th>
<th>Fuel B</th>
<th>Fuel C</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>9.03</td>
<td>8.83</td>
<td>8.46</td>
</tr>
<tr>
<td>ash</td>
<td>6.7</td>
<td>6.1</td>
<td>8.8</td>
</tr>
<tr>
<td>NCV</td>
<td>17.23</td>
<td>17.18</td>
<td>16.70</td>
</tr>
<tr>
<td>C</td>
<td>46.7</td>
<td>46.3</td>
<td>45.8</td>
</tr>
<tr>
<td>H</td>
<td>5.68</td>
<td>5.60</td>
<td>5.59</td>
</tr>
<tr>
<td>N</td>
<td>0.46</td>
<td>0.48</td>
<td>0.51</td>
</tr>
<tr>
<td>Al</td>
<td>260</td>
<td>3650</td>
<td>245</td>
</tr>
<tr>
<td>Ca</td>
<td>2410</td>
<td>2505</td>
<td>8660</td>
</tr>
<tr>
<td>Cl</td>
<td>847</td>
<td>817</td>
<td>1095</td>
</tr>
<tr>
<td>Fe</td>
<td>126</td>
<td>173</td>
<td>152</td>
</tr>
<tr>
<td>K</td>
<td>7435</td>
<td>6735</td>
<td>9375</td>
</tr>
<tr>
<td>Mg</td>
<td>661</td>
<td>573</td>
<td>3950</td>
</tr>
<tr>
<td>S</td>
<td>605</td>
<td>632</td>
<td>746</td>
</tr>
<tr>
<td>Si</td>
<td>17350</td>
<td>19050</td>
<td>15750</td>
</tr>
</tbody>
</table>

The variation of the water content during the experiments was found to be between 8.4% and 9.5% for all three types of pellets. The net calorific value varied between 16.6 MJ/kg and 17.3 MJ/kg.

The ash content was analysed repeatedly during the period of combustion experiments. Values were found to be slightly increased for Fuel C which can be explained with the addition of 3% additive. However, strong variations and also high values for straw without additive could be observed, from 5.0% (for Fuel B) to 8.1% (for Fuel A), most probably due to impurities or changes of the fuel quality.

#### 4.2 Combustion performance and gaseous emissions

All three fuels showed similar combustion behaviour: Although additives had been used to increase the ash melting temperatures of the straw-pellets, the slag formation tendency was very high. In spite of regular grate cleaning, lumps of slag accumulated in the combustion zone and had to be removed manually in regular intervals (every 3-5 hours) in order to sustain stable combustion conditions.

With regard to the burnout of the gaseous components, the combustion quality was very good. CO emissions measured during the combustion of all three fuels are comparable to the emissions of state-of-the-art wood pellet boilers [10]. Table IV shows average values for gaseous emissions under full load and part load operation, with a standard setting and also applying the Hydrocube® technology. Average values from all experiments are presented, since the emissions for NOx, SO2 and HCl were in the same range for all fuels.

Table IV: Emission values from the combustion of all three fuels under standard conditions and using the Hydrocube® (average values are calculated over intervals of several hours in each experiment)

<table>
<thead>
<tr>
<th>Emissions in mg/MJ</th>
<th>Full load</th>
<th>Part load</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO standard</td>
<td>56</td>
<td>79</td>
</tr>
<tr>
<td>CO with HC</td>
<td>47</td>
<td>65</td>
</tr>
<tr>
<td>NOx standard</td>
<td>228</td>
<td>212</td>
</tr>
<tr>
<td>NOx with HC</td>
<td>221</td>
<td>214</td>
</tr>
<tr>
<td>SO2 standard</td>
<td>56</td>
<td>53</td>
</tr>
<tr>
<td>SO2 with HC</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>HCl standard</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>HCl with HC</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

In average the CO emissions are below 100 mg/MJ and therefore comply with the threshold value of 500 mg/MJ according to the Austrian legislation [11]. Regarding the operating conditions, CO emissions are found to be slightly increased for part load operation.

NOx emissions are below the proposed threshold value for standardised non-wood solid biofuels of 300 mg/MJ [12] with average values of 212 mg/MJ to 228 mg/MJ and as expected no significant influence of the Hydrocube® application can be observed.

According to the Austrian legislation, no threshold values for SO2 or HCl in the flue gas are available. For both compounds, comparable concentrations were found in the flue gas during full load and part load operation with 53 – 56 mg/MJ SO2 and 11 – 14 mg/MJ HCl. During Hydrocube® operation a significant reduction of 81% for SO2 and of 68% for HCl was measured.

#### 4.3 Particulate emissions

In Table V average values for dust emissions and separation efficiency at different operating conditions are summarised. In general, dust emissions were found to be very low compared to previous measurements in other projects or results found in literature ([1][13][14]). Unexpectedly, straw pellets without additive showed the lowest values. It may be assumed that the variations in the fuel quality (cf. chapter 4.1) do influence the particle emissions. Additionally, it has been observed that slag formation in the combustion chamber has been significantly higher for Fuel A (straw only) than for the fuels with additives. As a consequence, it is assumed that the formation of particulates in general and the amount of coarse particles released from the slagging fuel belt in particular is lower compared to the experiments with less slag formation in the combustion chamber.

---

**Table II: Variations of the experimental program**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Standard</th>
<th>HC</th>
<th>eHC</th>
<th>HC-HE only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table III: Results from fuel analyses**

HC......Hydrocube®
HE......Heat exchanger
eHC...... Hydrocube® + electronic charger
further work is required to better explain this phenomenon.

Table V: Average dust emissions and separation efficiencies for all fuels at different operating conditions

<table>
<thead>
<tr>
<th>Load</th>
<th>Fuel A</th>
<th>Fuel B</th>
<th>Fuel C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL</td>
<td>Standard</td>
<td>68</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td>54</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>eHC</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>PL</td>
<td>Standard</td>
<td>n.d.</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td>n.d.</td>
<td>71</td>
</tr>
</tbody>
</table>

Separation efficiency in %

<table>
<thead>
<tr>
<th>Load</th>
<th>Fuel</th>
<th>Standard</th>
<th>HC</th>
<th>eHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL</td>
<td>HC</td>
<td>11</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>eHC</td>
<td>66</td>
<td>n.d.</td>
<td>61</td>
</tr>
<tr>
<td>PL</td>
<td>HC</td>
<td>n.d.</td>
<td>27</td>
<td>21</td>
</tr>
</tbody>
</table>

4.3.1 Influence of the operating conditions of the boiler

Compared to full load operation, slightly increased dust emissions were found under part load conditions.

Using the Hydrocube®, dust emissions could be reduced by 20% in average at full load operation, and thus barely comply with the threshold value of 60 mg/MJ for dust emissions from the combustion of standardised non-wooden biomass [12]. Under part load conditions, the separation efficiency was marginally higher. Anyway, due to slightly increased dust emissions under part load conditions, the threshold value of 60 mg/MJ was exceeded in most experiments.

Figure 3 shows average dust emissions from the combustion of Fuel B with and without the application of the Hydrocube® at full load and part load conditions. Moreover, the threshold value for the combustion of standardised non-wooden biomass according to [12] is specified.

4.3.2 Investigation of the Hydrocube®-technology

The Hydrocube®-technology was studied operating the original system, the system with an additionally implemented electronic charger, and the Hydrocube®-heat-exchanger without the condensate scrubber.

With the original system, an average (full load and part load) separation efficiency of 20 - 25% was reached. By applying the Hydrocube® with the additional electronic charger, the separation efficiency increased up to 66%. In Figure 5 results are shown for Fuel A and Fuel B at full load conditions.

The results of the gravimetric measurements showed higher values for part load operation, an increase of coarse particles can be assumed. Lower temperatures in the combustion chamber during part load operation can result in reduced formation of particles via volatilisation and subsequent condensation reactions (gas-to-particle conversion) [15]. At the same time, changes of the flow conditions in the fuel bed can lead to an increased entrainment of coarse particles (> 1 µm).

Dust samples have also been analysed with regard to their elemental composition. Figure 4 shows the results for dust emissions from the combustion of Fuel B.

In the dust from part load combustion, higher concentrations of carbon – especially of non-carbonate (organically bound) carbon – can be found: Carbonate related (inorganic) carbon increases from 0.02 - 0.12% under full load conditions to 0.7 - 2.0% during part load operation. Organically bound carbon increases from about 3% to 17% of total solid mass, which indicates a reduced burnout quality of gaseous components.

The main fraction of particles consists of potassium and chlorine, amounting to 93% under full load and 78 - 80% under part load regime. In addition 2.2 - 2.6% sulphur are found in the fuel. All other ash forming elements summed up are found to be around 0.8%.

Applying the Hydrocube® technology, only small changes could be observed with regard to the elemental composition: Carbonate carbon was reduced under both operating conditions, and among the small fraction of ash forming elements, a reduction of aluminium, iron, calcium and magnesium was measured.

Figure 4: Elemental composition of dust emissions from the combustion of Fuel B (100% = sum of elements without oxygen)

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Figure 5: Average values for dust emissions from the combustion of Fuel A and Fuel B under standard conditions and using the Hydrocube® technology, changes with regard to the particle size could be observed. The graphs in Figure 6 and Figure 7 show quantity distribution of particles as well as the mass of the particle fractions for dust emissions under standard conditions, using the Hydrocube® and the Hydrocube® heat exchanger only. Except the results for “Hydrocube® heat exchanger only”, where only one data set is available, the presented values are average values from different experiments.

From Figure 6 it is obvious that particles of particle diameters between 0.06 µm and 0.26 µm are significantly reduced when using the Hydrocube® and the Hydrocube® heat exchanger. Furthermore, a strong increase of the particle fraction of 0.03 µm is observed for both cases compared to standard operation. This increase in the number of particles might be explained with the solubility of single components, like e.g. KCl, in liquid aerosols, formed by condensation effects. Drying the flue gas, these aerosols can evaporate and thus submicron particles can be formed. A similar principle is used for a systematic particle generation (e.g. spray drying technologies). The analysis of the quantity size distribution does not allow any conclusions for particles > 0.4 µm due to the low number of particles detected. In general, eventual differences in the particle quantity distribution are not obvious between the experiments with Hydrocube® and with Hydrocube® heat exchanger.

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Between 80% and 90% of sulphur and chlorine and about 10% of potassium from the fuel could be recovered. For all three elements, the proportion that is released via dust emissions is not influenced by using the Hydrocube®. However, the release of sulfur and chlorine components via gaseous emissions is reduced significantly, and it can be seen, that almost the whole amount has been absorbed in the condensate.

The properties of the circulating condensate were investigated by a continuous measurement of the pH-value as well as elemental analyses. Figure 9 shows the developing of the concentration in the condensate with increasing operating time of the Hydrocube® scrubber for selected elements.

Figure 9: Enrichment of selected elements in the condensate with increasing operating time during the combustion of Fuel B

A clear increase of the concentration in the condensate was measured for sulphur, chlorine, potassium, iron, phosphorus, nickel, chromium, copper and zinc. The concentration of other elements like e.g. magnesium or calcium did not change during operation or were below the detection limit. The enrichment of most elements can be related to the uptake of gaseous compounds and particulate matter in the condensate. The quantity of chromium and nickel in the condensate is much higher than amounts that could have been released from the biomass used. Regarding the low pH-values of the condensate, a corrosive attack and consequently dissolution of the steel components can be assumed.

Due to an increasing absorption of acid gaseous compounds, the pH-value of the condensate decreased, approaching a value of about 2.5 after 7 hours of operation. Both pH-value and elemental concentration seem to approach a final value.

4.5 Energy balance

Using the Hydrocube® technology, heat from the flue gas is recovered and used on one hand to heat up the cold flow of the heating circuit, and on the other hand to provide hot water for domestic use. Table VI shows average values for the heat recovery that have been measured during the experiment, referring to a heat input of 16 kW and a cold flow temperature of the heating circuit of 50 deg C.

Table VI: Energy recovery using the Hydrocube®

<table>
<thead>
<tr>
<th>Energy recovery from the flue gas in %</th>
<th>Full load</th>
<th>Part load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat used for hot water</td>
<td>6.8</td>
<td>7.7</td>
</tr>
<tr>
<td>Heat returned to the heating circuit</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Total Energy recovery</td>
<td>10.6</td>
<td>10.2</td>
</tr>
</tbody>
</table>

In average, the efficiency of the system could be increased by 10%, which is in accordance with the results of Rawe et al. [18].

5 SUMMARY AND CONCLUSIONS

All three fuels showed a high slag formation tendency, and the influence of the additives was weak compared to the effect of variations of the fuel quality. In all experiments emissions complied with the threshold values for CO and NOx according to the Austrian legislation [11][12].

Dust emissions of 70 - 100 mg/MJ were relatively low (cf. [1][13][14]), but exceeded the threshold value of 60 mg/MJ in many cases. During part load operation they were slightly increased and showed higher concentrations of organic and inorganic carbon.

By applying the Hydrocube® technology, dust emissions could be reduced by 20 - 25%. A reduction was determined for particles in the range of 0.06 – 0.26 µm and for coarse particles, and variations showed, that the main segregation effect for fine particles is due to the heat exchanger of the Hydrocube®. In contrary to the reduction of most particle fractions, a strong increase of the 30 nm fraction was measured, when operating both the Hydrocube® and the heat exchanger only. The contribution of this fraction to the total solid mass is negligible, but could be important regarding health effects. For an optimisation of the technology, further investigations concerning the mechanism of the particle formation will be required.

Variations of the Hydrocube® technology with an additionally implemented electronic charger resulted in an increase of the separation efficiency up to 65%. For further optimisation, a parameter study would be required in order to identify the effectiveness of each part of the system.

The elemental composition of the dust was hardly changed by the Hydrocube® application. Moreover, an elemental balance shows that gaseous components are absorbed by the condensate, and by this, harmful components like SO2 or HCl in the flue gas are reduced.

In the condensate, an enrichment of elements like sulphur, chlorine or potassium but also copper or zinc were observed. Moreover, very high concentrations for the heavy metals chromium and nickel along with a decreasing pH-value have been related to the corrosion of the Hydrocube® material. These results have to be taken into account when discussing the discharge of the condensate into municipal wastewater, but also regarding acidity-related corrosion effects of the Hydrocube® system.

Assuming that there is a final value for elemental concentrations as well as the pH-value, long term experiments should be conducted to investigate the
potential to remove harmful components from the flue gas but also corrosion reactions under stationary conditions. A regeneration of the condensate could pose a further challenge regarding the investigated technology.

With regard to energy efficiency, an average increase of the heat output of 10% was measured, when using the heat from the heat exchanger and the heat from the condensate circuit. The increase of energy efficiency is an important factor regarding the cost-effectiveness of the system. In order to benefit from this added value, an adequate implementation of the Hydrocube® into the heating system is required.

6 ACKNOWLEDGEMENT

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7 REFERENCES


