Performance of a pellet boiler fired with agricultural fuels

Lara Carvalho, Elisabeth Wopienka, Christian Pointner, Joakim Lundgren, Vijay Kumar Verma, Walter Haslinger, Christoph Schmidl

Bioenergy 2020+ GmbH, Gewerbepark Haag 3, 3250 Wieselburg-Land, Austria
Division of Energy Science, Luleå University of Technology, 971 84 Luleå, Sweden

HIGHLIGHTS

- Performance evaluation of a pellet boiler operated with different agricultural fuels.
- Agricultural fuels could be burned in the tested boiler for a certain period of time.
- All the fuels (except straw and Sorghum) satisfied the European legal requirements.
- Boilers for burning agricultural fuels should have a flexible control system.

ABSTRACT

The increasing demand for woody biomass increases the price of this limited resource, motivating the growing interest in using woody materials of lower quality as well as non-woody biomass fuels for heat production in Europe. The challenges in using non-woody biomass as fuels are related to the variability of the chemical composition and in certain fuel properties that may induce problems during combustion. The objective of this work has been to evaluate the technical and environmental performance of a 15 kW pellet boiler when operated with different pelletized biomass fuels, namely straw (Triticum aestivum), Miscanthus (Miscanthus × giganteus), maize (Zea mays), wheat bran, vineyard pruning (from Vitis vinifera), hay, Sorghum (Sorghum bicolor) and wood (from Picea abies) with 5% rye flour. The gaseous and dust emissions as well as the boiler efficiency were investigated and compared with the legal requirements defined in the FprEN 303-5 (final draft of the European standard 303-5). It was found that the boiler control should be improved to better adapt the combustion conditions to the different properties of the agricultural fuels. Additionally, there is a need for a frequent cleaning of the heat exchangers in boilers operated with agricultural fuels to avoid efficiency drops after short term operation. All the agricultural fuels satisfied the legal requirements defined in the FprEN 303-5, with the exception of dust emissions during combustion of straw and Sorghum. Miscanthus and vineyard pruning were the best fuels tested showing comparable emission values to wood combustion.

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1. Introduction

During the last 30 years, small-scale wood combustion systems have been well developed and reached a high quality and performance level in Europe. The energy efficiency has increased, the emissions have decreased, fully automatic operation systems have been developed and the combustion technology has been optimised for woody biomass fuels [1,2]. Automatically stoked systems are normally based on staged combustion, i.e. two main combustion zones are created in order to maximise the burnout rates. The primary combustion zone is located on a grate or burner plate where drying, devolatilization and char combustion takes place. The secondary combustion zone is located above the grate in the combustion chamber where the combustible gases are oxidised [2,3]. Furthermore, each combustion zone has its own air supply; primary and secondary air are supplied in the fuel bed and in the combustion chamber [4]. In this way, automatic pellet boilers can show efficiencies higher than 90% (based on the lower heating value) with CO emissions below 50 mg Nm⁻³ at 13 vol.% O₂ [3] (which corresponds to approximately 46 mg MJ⁻¹) under steady state combustion conditions.

Presently, the market for fossil fuels is unstable and their prices are constantly rising. Furthermore, Europe has the target of reaching its share of renewable energies to 20% by 2020 [5] and biomass can play an important role. However, the increasing competition...
for woody biomass in the heating sector, sawmills and pulp and paper industries are increasing the price of wood [6]. As a result, the interest for alternative biomass fuels is growing rapidly, covering woody materials of low quality, energy crops and agricultural and forest residues [7–12]. There are several benefits from expanding the spectrum of biomass raw materials used in small-scale combustion systems [13]. Besides increasing the use of renewable energies, energy crops can provide a supplemental income for farmers and at the same time show the potential of restoring degraded lands, preventing soil erosion. The value of the agricultural and forest residues can be increased by using them as fuels and more job opportunities for power and agricultural equipment industries can be created. However, burning non-woody biomass fuels in small-scale heating systems is a challenging option [11,14,15]. Compared to wood, non-woody biomass assortments have higher ash contents and a higher content of critical inorganic elements. Ash related problems are therefore expected, which affect the dust emissions [16] and cause problems during combustion due to e.g. slagging [10,17]. Slag on the grate of small-scale pellet boilers may disturb the combustion process (e.g. higher CO emissions [11]) and lead to unwanted shutdowns of the boiler [18]. High concentrations of nitrogen (N), sulphur (S) and chlorine (Cl) in agricultural fuels increase the emissions of nitrogen oxides (NOx), sulphur dioxide (SO2) and hydrogen chloride (HCl), respectively [4,16]; they may also cause the formation of dioxins and furans under certain combustion conditions, e.g. intermittent combustion [19,20]. Nitrogen oxides can be formed during combustion by three mechanisms referred to as thermal, prompt and fuel-bound NOx. The thermal and prompt NOx formation paths become active at temperatures above 1300 °C [21] which are normally not reached in small-scale combustion systems. Consequently, nitrogen oxides are assumed to be formed mainly from fuel nitrogen during biomass combustion and therefore cannot be completely avoided [21,22]. Minimisation of NOx emissions by optimising the combustion conditions is however possible by air or fuel staging [4,16]. The release of SO2 and to a lesser extent SO3 results from the oxidation of the fuel sulphur [11,16]. These emissions are usually not significant for wood combustion due to the low sulphur contents of the fuel. However, at sulphur concentrations higher than 0.2 wt.% dry basis, SO2 emissions start to be relevant due to its important role in corrosion [16]. Both NOx and SO2 have significant health effects (e.g. respiratory problems) [23] and are harmful gases to the environment contributing to acid rain. Incomplete combustion can lead to emissions of carbon monoxide (CO), OGC (organic gaseous carbon), PAH (polyaromatic hydrocarbons), soot and tar. CO is generally considered an indicator of the combustion quality for the reason that it is oxidised to CO2 in the presence of oxygen and at a rate which depends on the combustion temperature, residence time and mixing rate between the combustible gaseous species from the fuel and air [3,4,16]. Biomass combustion also leads to relatively high dust emissions. Wood burning is one of the major contributors of primary particle to the atmosphere during winter times over large parts of Europe [24–28]. Small-scale combustion systems in particular play an important role [26–28]. The dust emissions can consist of both carbonaceous particles and vapourised inorganic matter mainly alkaline metals, sulphur and chlorine. Under poor combustion operation practices such as unsatisfactory air supply occurring for instance in old residential heating appliances [29,30], the dust emissions are high and dominated by particles of incomplete combustion. Typical dust emissions from modern pellet boilers operated at 100% load can vary from 10 to 30 mg MJ−1, while the emissions from old residential heating appliances are between 65 and 150 mg MJ−1 or even higher [29,30]. The inorganic part always remains as background constituents. Efficient combustion of wood results in mainly inorganic fine particles [30,31] typically dominated by alkaline metals, such as potassium sulphates, chlorides and carbonates [32,33]. An increase in dust emissions is therefore expected when agricultural fuels are burned due to their high content of alkaline metals. The release of alkali metals is in turn influenced by other fuel elements present in agricultural fuels, most importantly chlorine, silicon and sulfur. While chlorine content enhances the release of alkali metals due to the formation of volatile alkali metal chlorides, silicates can react with potassium preventing its vapourisation [34,35]. Furthermore, sulphur in the fuel may inhibit the effect of chlorine through a sulfation reaction, in which the alkali metal chloride is converted to less volatile alkali metal sulphate [36]. The emissions and ash related problems during combustion of agricultural residues in medium and large scale combustion plants have been thoroughly investigated, e.g. [37–39]. However, there is still insufficient information available regarding their suitability in small-scale systems and whether they can be burned in accordance to the existing threshold values. Combustion of woody biomass causes emissions of gases and particulate matter which can seriously affect human health [23,40]. The introduction of new biomass fuels that potentially may cause higher emissions into the residential heating sector should be first thoroughly evaluated based on results from combustion tests. Furthermore, it is important to investigate the capability of the existing small-scale technologies in burning non-woody biomass fuels. Combustion tests provide important information to boiler manufactures by showing the limitations of the existing boiler technology and by identifying important parameters and improvements required to adapt them for a broader spectrum of biomass fuels.

The objectives of the present study are (i) to evaluate the technical and environmental performance of a 15 kW wood pellet boiler when burning different agricultural biomass fuels and (ii) to investigate the feasibility of different agricultural fuels for residential heat production. The feasibility study was done by comparing the gaseous and particle emissions as well as the boiler efficiency with the legal requirements defined in the FprEN 303-5 (final draft of the European Standard 303-5, Heating boilers – Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW – terminology, requirements, testing and marking) [41].

2. Material and methods

2.1. Fuel properties

The combustion tests were done with pelletized fuels from wood (Picea abies) with 5% rye flour and seven agricultural raw materials: straw from wheat (Triticum aestivum), Miscanthus (Miscanthus × giganteus), maize (Zea mays), vineyard pruning (from Vitis vinifera), wheat bran, hay and Sorghum (Sorghum bicolor). Straw was harvested in the Spring of 2006. Miscanthus was harvested between January and March of 2006. Maize was harvested in the Spring of 2006 and all the plant (stem and cob with maize grains) was pelletized. Wheat bran is the hard outer layer of a wheat grain. It is normally a by-product of milling in the production of refined wheat flour. Hay is a mixture of grasses, legumes and/or other herbaceous plants. Its composition depends greatly on the region where it grows. Detailed information about the Sorghum pellets tested is given elsewhere [42]. No information regarding the place of growth and the time of harvesting is available for the pellets from vineyard pruning, wheat bran and hay.

Chemical and thermal properties of each of the experimental pellets were analysed according to the relevant standard methods and the properties are presented in Table 1. The ash and moisture contents of the pellets were analysed according to CEN/TS 14775,
at 550 °C and DIN 51718, respectively. The lower heating value (LHV) was calculated from the HHV based on the moisture content of each fuel. The higher heating value (HHV) was determined using an adiabatic bomb calorimeter according to ÖNORM CEN/TS 14918. The content of the major elements, carbon (C) and nitrogen (N) were determined according to prCEN/TS 15104. The total sulphur (S) was determined using the CEN/TS 15289 method. The oxygen (O) content was calculated by difference according to Eq. (1).

\[ O(\text{wt%}) = 100 - (\text{Ash} + C + H + N + S) \]  

The ash forming elements (cations) were determined by microwave digestion. The Cl content was determined by analyzing a solution of the combustion gases dissolved in deionized water via IC.

**2.2. Combustion equipment**

The combustion tests were performed in a commercially available pellet boiler illustrated in Fig. 1. The boiler had a nominal thermal capacity of 15 kW and was equipped with a lambda sensor (LSM 11). Primary combustion air was supplied from below the grate and secondary air from above the fuel bed. The boiler had a horizontal feed burner with fuel pellets supply via a horizontal feed screw. The ash removal was done by the conveying fuel and by a horizontal movement of the grate. On the opposite side of the fuel feeding there was an opening where the ash residues fell down into the ash box, placed below the grate. In the opening there was an agitator that rotated perpendicularly to the fuel and ash transport and destroyed possible ash lumps and slag. The agitator was not included in the commercial version. Several combustion

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**Table 1**

Properties of the investigated pellets.

<table>
<thead>
<tr>
<th></th>
<th>Wood with 5% rye flour</th>
<th>Straw</th>
<th>Miscanthus</th>
<th>Maize</th>
<th>Vineyard pruning</th>
<th>Hay</th>
<th>Wheat bran</th>
<th>Sorghum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>LHV (MJ kg⁻¹) dry basis</td>
<td>18.90</td>
<td>15.78</td>
<td>16.09</td>
<td>15.74</td>
<td>16.50</td>
<td>15.46</td>
<td>15.18</td>
<td>15.95</td>
</tr>
<tr>
<td>Moisture (wt.%)</td>
<td>10.2</td>
<td>7.9</td>
<td>8.7</td>
<td>8.7</td>
<td>8.4</td>
<td>7.5</td>
<td>13.7</td>
<td>7.9</td>
</tr>
<tr>
<td>Ash (wt.%)db</td>
<td>0.21</td>
<td>5.71</td>
<td>3.26</td>
<td>3.39</td>
<td>2.70</td>
<td>7.40</td>
<td>5.70</td>
<td>7.90</td>
</tr>
</tbody>
</table>

**Proximate analysis (wt.% dry basis)**

<table>
<thead>
<tr>
<th></th>
<th>Carbon (C)</th>
<th>Hydrogen (H)</th>
<th>Nitrogen (N)</th>
<th>Sulphur (S)</th>
<th>Oxygen (O)</th>
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<tr>
<td></td>
<td>47.1</td>
<td>6.17</td>
<td>0.19</td>
<td>0.10</td>
<td>46.3</td>
</tr>
<tr>
<td></td>
<td>47.30</td>
<td>5.80</td>
<td>0.66</td>
<td>0.10</td>
<td>40.43</td>
</tr>
<tr>
<td></td>
<td>47.30</td>
<td>6.00</td>
<td>0.24</td>
<td>0.03</td>
<td>43.17</td>
</tr>
<tr>
<td></td>
<td>45.9</td>
<td>6.36</td>
<td>0.89</td>
<td>0.09</td>
<td>43.17</td>
</tr>
<tr>
<td></td>
<td>45.71</td>
<td>6.30</td>
<td>0.39</td>
<td>0</td>
<td>43.43</td>
</tr>
<tr>
<td></td>
<td>45.94</td>
<td>5.72</td>
<td>1.07</td>
<td>0.13</td>
<td>43.84</td>
</tr>
<tr>
<td></td>
<td>46.40</td>
<td>6.08</td>
<td>3.04</td>
<td>0.24</td>
<td>38.54</td>
</tr>
<tr>
<td></td>
<td>46.90</td>
<td>5.81</td>
<td>1.08</td>
<td>0.11</td>
<td>38.20</td>
</tr>
</tbody>
</table>

**Inorganic species of the fuels (mg kg⁻¹ fuel) dry basis (relevant for the present study)**

<table>
<thead>
<tr>
<th></th>
<th>Alkali metals (K + Na)</th>
<th>Alkali earth metals (Ca + Mg)</th>
<th>Chlorine (Cl)</th>
<th>Silicon (Si)</th>
<th>Phosphorous (P)</th>
<th>Zink (Zn)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n.d.</td>
<td>14130</td>
<td>3342</td>
<td>1720</td>
<td>716</td>
<td>n.d.</td>
</tr>
<tr>
<td></td>
<td>1012</td>
<td>2613</td>
<td>214</td>
<td>9829</td>
<td>318</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>7867</td>
<td>2003</td>
<td>1024</td>
<td>3613</td>
<td>1999</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>n.d.</td>
<td>8806</td>
<td>1090</td>
<td>12600</td>
<td>2460</td>
<td>n.d.</td>
</tr>
<tr>
<td></td>
<td>274649</td>
<td>16140</td>
<td>15614</td>
<td>174561</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

a LHV – low heating value; n.d. – not determined.
parameters could be set in the boiler control. The relevant and modified parameters for the combustion tests were: air ratio, fuel load and grate movement. The grate movement parameters controlled the frequency and the period of the movements.

2.3. Experimental test setup

The combustion tests were performed at the laboratory of Bioenergy 2020+, Lower Austria (48.117°N 15.136°E, 270 m above mean sea level). The combustion tests with each type of pellets were planned to last a minimum of 8–12 h in steady-state conditions. A schematic of the experimental setup is presented in Fig. 2.

The temperatures in the combustion chamber and of the flue gas \(T_{fg}\) were continuously monitored using K-type thermocouples. The feed and hot water temperatures \(T_{FW}\) and \(T_{HW}\) were maintained at 55°C (±2°C) and 75°C (±2°C) respectively and were monitored using Pt-100 thermocouples. The chimney draft \(P\) was continuously measured using a pressure transmitter PTL2-K. The data was acquired every second during the steady-state operation of the boiler and average values were calculated for periods of 1 h.

The settings used for the moving grate, air ratio and fuel load are presented in Table 2.

Different settings for the grate movement parameters were used in the combustion tests with wood and agricultural fuels, owing to their large differences in ash contents. The difference in fuel load during wheat bran and Shorgum combustion is explained in Section 3.1.1.

### Table 2

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Moving grate</th>
<th>Air ratio</th>
<th>Fuel load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency of the movement (h⁻¹)</td>
<td>Movement duration (s)</td>
<td></td>
</tr>
<tr>
<td>Wood with 5% rye flour</td>
<td>0.5</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Straw, Miscanthus, maize, vineyard pruning and hay</td>
<td>36</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Wheat bran</td>
<td>36</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Sorghum</td>
<td>36</td>
<td>1.5</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic layout of the experimental setup.

2.3.1. Measurement of gaseous and particulate emissions

A constant flow of flue gas (0.8 L s⁻¹) was extracted and transported to the gas analyser (NGA 2000) through heated sampling probes and lines. The concentrations of CO₂, O₂, NO₂, NO, SO₂ and CO in the flue gas were continuously monitored. The measurement principles of the gas analyser were paramagnetic for O₂, non-dispersive infra-red for CO, NO, and CO₂, and ultraviolet cell for SO₂ and NO₂ determinations. The gaseous emissions were acquired every second. The particulate matter was sampled isokinetically using a gravimetric method as described in VDI 2066/sheet 2 (Measurement of particulate matter in flowing gases). The total coarse and the major fine dust fraction in the flue gas were collected in a cartridge filter of quartz wool. The particulate matter was sampled at least three times in each experiment. The emission values were converted to mg MJ⁻¹ of fuel heat input.

2.3.2. Measurements of the fuel mass flow

The boiler was placed on a scale (Mettler Toledo PTA with an accuracy of 0.04–0.3 kg) in order to determine the amount of fuel used during each combustion test (see Fig. 2). The mass flow of fuel on the grate was calculated for each experiment by dividing the total amount of burned fuel by the total time of the combustion test. The mass flow of ash on the grate was calculated based on the ash content of each fuel and by subtracting the amount of ash lost in the form of dust emissions.

2.3.3. Slag tendency measurements

The slag tendency of a biomass fuel was analysed through sieving, as described in [43]. The ash from the ash box was sieved at the end of each combustion test. The ash particles retained in the sieve of 5.6 mm mesh size were considered slag. The percentage of slag in the ash was calculated for each test.
2.4. CO and NO\textsubscript{x} versus lambda

The lambda probe allowed the boiler to operate at a relatively constant lambda value. However, small lambda variations (2.0 ± 0.3) were observed during the combustion tests. These variations were most probably due to the type of lambda probe used by the boiler (see Section 2.2) which has a high resolution signal for lambdas around one. Continuous measurements of CO and NO\textsubscript{x} acquired during combustion could therefore be compared to the variations in the lambda value.

2.5. Efficiency

The boiler efficiency was calculated using an indirect method by measuring the losses occurring in the boiler as follows.

\[
\eta_{\text{Indirect Method}}[\%] = 100 - (q_A + q_U + q_F + q_S)
\]

In Eq. (2), \(q_A(\%)\) is the thermal loss in the flue gas, \(q_U(\%)\) is the loss due to unburned fuel carbon in the flue gas, \(q_F(\%)\) is the loss due to unburned carbon in the solid residue (ash) and \(q_S(\%)\) is the radiation heat loss from the boiler surface. \(q_A\) and \(q_U\) were calculated using Eqs. (3) and (4) respectively.

\[
q_A = \frac{(V_{fg,d} c_{pfg} + V_w c_{pwater})(T_{fg} - T_{air})}{LHV}
\]  

\[
q_U = 10^{-6} CO_{gen} V_{fg,d} \frac{12640}{LHV}
\]

Here, \(V_{fg,d}(m^3\ \text{kg}^{-1})\) is the volume of dry flue gas generated during combustion per kg of fuel, \(V_w(m^3\ \text{kg}^{-1})\) is the volume of moisture in the flue gas, \(T_{fg}(^\circ\text{C})\) and \(T_{air}(^\circ\text{C})\) are the temperatures of the flue gas and ambient air respectively, \(c_{pfg}(kJ\ (kg\ K)^{-1})\) and \(c_{pwater}(kJ\ (kg\ K)^{-1})\) are the specific heat capacities of the flue gas and water respectively and \(CO_{gen}(ml\ m^{-1})\) is the CO content in the flue gas.

The loss due to unburned carbon in the ash \((q_F)\) was determined for wood pellets and other agricultural fuels, e.g. Sorghum and were below 0.02%. The influence of this loss on the efficiency was considered irrelevant and therefore \(q_F\) was assumed zero in the efficiency calculations (Eq. (2)).

The radiation heat loss from the boiler surface \((q_S)\) was assumed to be 1% of the total heat output, as stated in the boiler user’s manual.

![Graphs showing CO emissions as a function of the excess air ratio.](image-url)
3. Results and discussions

The results of the combustion tests are presented and discussed with regard to boiler technology aspects, emissions and efficiency.

3.1. Boiler technology aspects

Three important aspects of the boiler technology, (1) fuel feeding, (2) air ratio and (3) ash management, are presented and discussed.

3.1.1. Fuel feeding

The combustion tests were performed at full load, i.e. at 100% fuel feeding, with the exception of the tests with wheat bran and Sorghum pellets, performed at 50% and 75% load respectively, as shown in Table 2. The reason for the reduced loads was that both wheat bran and Sorghum burned out more slowly than the other biomass fuels. As a result, a stable fire bed could not be formed between two consecutive movements of the grate and unforeseen shut downs of the boiler were continuously occurring. The fuel load of wheat bran and Sorghum were therefore reduced until a continuous operation for the stipulated amount of time was possible.

Considering only the fuels operated at 100% nominal load and with equivalent operating settings of the fuel screw, the mass flow of fuel varied considerably when different fuels were used (Table 3). Fuel mass flows ranging from 3.62 to 4.45 kg h\(^{-1}\) were observed, corresponding to a variation of approximately 20%. As a result, the energy input to the boiler also varied considerably and proportionally to the mass flow of fuel. The energy load ranged from 15.83 kW with maize to 20.39 kW with vineyard pruning. The variability in both mass and energy flows can be explained by differences in the bulk density. Pelletized agricultural and forestry biomass commonly show bulk densities ranging from 480 to 700 kg m\(^{-3}\) [11,44–48]. Other factors that may influence the fuel feeding are pellet size [46], amount of fines [47] and the surface of the pellets [47]. The mass flow of ash varied between 0.12 and 0.31 kg h\(^{-1}\) due to different fuel mass flows and different ash contents of the experimental fuels (ash contents ranging from 3.3 to 7.9 wt.% dry basis in Miscanthus and Sorghum respectively).

3.1.2. Excess air ratio

Each combustion unit has a characteristic CO versus air ratio curve when operated with a certain biomass fuel. Such curves give the air ratio that minimises emissions and maximises the efficiency. Furthermore, to ensure a complete combustion, a good utilisation of the combustion chamber (with even gas flow distribution) as well uniform temperature distribution (avoiding local temperature peaks) should be achieved by optimising the combustion chamber and nozzle geometries [40]. Therefore, the CO characteristics can also be used to assess the suitability of the combustion chamber dimensions in burning a specific fuel. Fig. 3 illustrates the CO versus excess air ratio curves for each of the investigated biomass fuels for the applied combustion unit.

Most of the biomass fuels show a clear and smooth CO characteristic curve. As expected, each side of the curves show a sharp and a gradual increase of the CO emissions at low and high excess air ratios respectively.

In the present boiler, the minimum CO emissions are obtained at excess air ratios of 1.6–1.8 for Miscanthus and maize, 1.8–2.0 for vineyard pruning, 1.9–2.1 for hay and Sorghum and 2.0–2.2 for wheat bran. The CO emissions were consistently high for straw pellets relative to the other fuels. Therefore, the most favourable excess air ratio interval to minimise CO emissions was not clear. Nevertheless, the lowest CO emissions for straw pellets were obtained at excess air ratios of 2.0–2.1. The high variability of the CO emissions exhibited by straw and to a smaller extent by wheat bran and maize, indicates a difficulty of the boiler in achieving stable combustion conditions with these fuels.

Several reasons can explain the differences in the excess air ratios to minimise CO emissions found for each fuel, (i) the combustion chamber was designed for woody fuels and therefore, their size and shape were not optimal for all the fuels; (ii) the residence time on the grate was not optimal for all the pellets; (iii) slagging and ash lumping on the grate; (iv) the boiler control does not fully adapt the burning conditions to the different biomass fuels. The boiler was operated at lambda values averaging 2.0 however, the plots of Fig. 3 showed that some of the fuels required lower or higher air ratios in order to minimise CO emissions.

3.1.3. Managing high ash contents

3.1.3.1. Ash and slag. Slag is sintered ash formed on or near the grate and which strength (i.e. degree of sintering) is mostly affected by the fuels composition [17]. Ash caking and slag was formed in different amounts during the combustion tests. The percentage of slag present in the ash of straw, maize, Sorghum and wheat bran ranged from 20% to 45% while the ash from Miscanthus, vineyard pruning and hay exhibited values of slag below 1%. Further discussion on the different slagging behaviours of the fuels is given in [43]. The boiler was able to effectively remove the ash lumps and slag from the grate due to the moving grate and the agitator (not included in the commercial version), allowing the boiler to operate for the stipulated time period of 8–12 h.

3.1.3.2. Ash depositions on the heat exchanger surfaces. Combustion-generated fly ash particles are responsible for ash deposition on the heat transfer surfaces which will lead to reduced heat transfer [38,39]. In the present study, several consecutive combustion tests with different fuels were performed without cleaning the heat exchanger between the tests. During these test runs, a progressive

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Heat exchanger not cleaned between tests</th>
<th>Heat exchanger cleaned between test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accumulated operational time of the boiler (h)</td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>39</td>
<td>89.2</td>
</tr>
<tr>
<td>Straw</td>
<td>55</td>
<td>88.4(^a)</td>
</tr>
<tr>
<td>Miscanthus with additive(^a)</td>
<td>63</td>
<td>89.6</td>
</tr>
<tr>
<td>Maize</td>
<td>85</td>
<td>81.7(^c)</td>
</tr>
<tr>
<td>Straw with additive(^a)</td>
<td>110</td>
<td>79.9</td>
</tr>
</tbody>
</table>

\(^a\) The combustion tests with pellets containing additives were outside the scope of the present work. However, they were one of the fuels tested without cleaning of the heat exchangers. The efficiency results were therefore important to show the built of deposits.

\(^b\) The flue gas temperature increased with 5 °C in approximately 5 h.

\(^c\) The flue gas temperature increased with 10 °C in approximately 7 h.
increase in flue gas temperature was observed. After a total operational time of 110 h, the boiler efficiency had decreased with approximately 10%, due to the continuous build up of deposition on the heat exchanger walls that inhibited proper heat transfer between the flue gas and the feed water. Table 4 shows the effect of cleaning the heat transfer surface on the boiler efficiency during combustion of different fuels.

The efficiencies shown in Table 4 were calculated based on the heat input and output of the boiler (direct method), owing to the inaccuracy of the indirect method in these particular cases. Efficiency drops due to the accumulation of ash particles in the heat exchanger walls can be avoided by frequently cleaning the heat exchangers.

### 3.2. Boiler limitations and potential improvements

Three main boiler limitations were found when agricultural biomass fuels were burned in the wood pellet boiler. The first was connected to the combustion chamber; based on the results of the CO characteristic curves shown and explained in Section 3.1.2, the design of the combustion chamber was most probably not optimal for all the agricultural fuels. The second limitation was related to the boiler lambda control; the boiler was unable to adjust to an optimal excess air ratio. The optimum lambda value for some of the fuels was either lower or higher than the one the boiler was using (1.9–2.0). Finally, the third boiler limitation was related to the heat exchangers. It was observed that in consecutive combustion tests, the efficiency was progressively decreasing due to ash accumulation on the heat exchangers.

Several modifications in the boiler technology are required to improve the combustion of agricultural fuels. The boiler control system should be more flexible in order to better adapt the burning conditions to the different fuels. That could be done, e.g., by improving the control algorithm of the boiler so that the operation settings are changed according to the fuel type. The user could insert key fuel properties or the system could have a database with the different fuel properties and the user would only need to choose the fuel type prior to combustion. The boiler would then adapt the air supply and fuel feeding to the desired heat output. In this way, the problems related with the combustion chamber design would also be reduced. Finally, heat exchangers with automatic cleaning systems would be recommended in the interest of keeping the high comfort and low maintenance level of the present boiler. The mechanisms for cleaning of the heat exchanger and moving grate could be connected to the controlling unit and the cleaning intervals would be a function of the fuel type.

### 3.3. Emissions

The gaseous and particulate emissions are presented and compared with the legal requirements defined in FprEN 303-5 [41].

#### 3.3.1. CO emissions

The CO emissions varied significantly among the studied agricultural fuels and were in general higher than when woody biomass was used, with the exception of Miscanthus (Fig. 4). Hay, wheat bran and straw pellets showed the highest values of 280, 224 and 223 mg MJ\(^{-1}\) respectively, which were eleven to fourteen times higher than the emissions from wood pellets. The CO emissions from maize, vineyard pruning and Sorghum were comparatively low and just two to five times higher than the emissions from wood pellets.

The difference in CO emissions between agricultural and woody fuels can be explained by the control system of the boiler, i.e. the boiler could not adapt the combustion air to the needs of the different agricultural fuels, as verified in Section 3.1.2. For example, wheat bran and hay were burned at an excess air ratio of 2.0. However, a reduction in the CO emissions is to be expected if the boiler would be operated at a lambda value of 2.1 with both fuels (Fig. 3). Additionally, the CO emissions observed during combustion of straw and wheat bran could be partly explained by the slag formed, whereas 40% and 37% of the ash from straw and wheat bran respectively, consisted of slag (Fig. 4). The formation of ash lumps and slag could have caused an uneven flow of combustion air through the fuel bed which could in turn impair the char and gas-phase burnout.

The FprEN 303-5 defines CO emissions for automatic stoked boilers with a nominal heat output below 500 kW operated with biogenic fuels. The CO emissions legal requirements for boiler classes 3, 4 and 5 are 3000 mg m\(^{-3}\) at 10% O\(_2\) (approximately 2000 mg MJ\(^{-1}\)), 1000 mg m\(^{-3}\) at 10% O\(_2\) (approximately 670 mg MJ\(^{-1}\)) and 500 mg m\(^{-3}\) at 10% O\(_2\) (approximately 330 mg MJ\(^{-1}\)).

![Fig. 4. CO emissions in units of mg MJ\(^{-1}\) and percentage of slag particles in the ash of the different fuels. The error bars correspond to the SEM (standard error of the mean).](image-url)
respectively. All the fuels tested can fulfill the CO emissions legal requirements for the three boiler classes.

3.3.2. NO\textsubscript{x} emissions

Fig. 5 shows the NO\textsubscript{x} emissions and the nitrogen conversion rate as a function of the different nitrogen contents of the agricultural fuels tested. The combustion temperatures were below 1300 °C and therefore the NO\textsubscript{x} emissions are expected to be only due to variations in the nitrogen bound in the fuel [4,21]. As expected, the NO\textsubscript{x} emissions show a growing trend towards higher fuel nitrogen contents. However, the two quantities were weakly correlated, as also observed by other authors, e.g. [7,11,49]. The weak correlation can have several explanations. On the one hand, high concentrations of CO or other carbon compounds may inhibit NO\textsubscript{x} formation [50,51]. Carbon monoxide has been shown to enhance the rate of NO reduction over different carbonaceous materials [52,53]. On the other hand, the catalytic effect of char and ash may also influence the NO\textsubscript{x} emissions [39,50]; the NO formed by the char may be re-adsorbed on the char surface and form N\textsubscript{2} by a following reaction with NO or NO can be reduced by CO catalysed by char [22]. The minerals present in biomass may enhance the rate of the NO char reaction, indicating a potential of this reaction for NO\textsubscript{x} control [53]. Consequently the catalytic effect of char must be taken into account in fuels with high ash contents [54] and in fuels with high content of catalytic active substances like calcium, magnesium, iron and potassium [22,39,55].

The combustion of agricultural fuels resulted in higher NO\textsubscript{x} emissions than when woody fuels were burned. In terms of legal requirements, the FprEN 303-5 [41] does not define NO\textsubscript{x} emission limits. Among the country deviations stated in the same draft standard, Austria is the only European country with legal NO\textsubscript{x} emissions requirements for boilers with a nominal heat output below 150 kW operated with standardised non-woody fuels. All the tested agricultural fuels, with the exception of maize, fulfil the NO\textsubscript{x} emission legal requirements (300 mg MJ\textsuperscript{-1}) according to the Austrian law.

The plots in Fig. 6 show the effect of the lambda variation on the NO\textsubscript{x} emissions. When maize was burned at a lambda of 1.7, the NO\textsubscript{x} emissions were reduced with about 22% to 270 mg MJ\textsuperscript{-1} without compromising complete combustion (see Section 3.1.2). In this way, maize was compliant with the Austrian legal requirements in terms of NO\textsubscript{x} emissions. Similarly, Miscanthus operated at a lambda of 1.6–1.7 would reach a 16% reduction in NO\textsubscript{x} emissions to about 175 mg MJ\textsuperscript{-1}. It can also be observed that when the boiler was operated at a lambda of 2.1 with hay and wheat bran instead of 2.0, which was found to be the optimal level in terms of CO emissions (see Section 3.1.2), the NO\textsubscript{x} emissions would increase with approximately 18% and 6% respectively, making wheat bran compliant with the Austrian NO\textsubscript{x} emission requirement. The
reductions and increases on the NOx emissions when the air ratio was decreased and increased respectively were probably connected with the conditions in the primary combustion zone. It is well known that a considerable reduction of the NOx emissions can be reached by applying staged combustion, i.e. creating an understoichiometric primary combustion zone and providing a mean residence time of 0.5 s between primary and secondary combustion will favour the reduction of fuel-N to N2 [4].

3.3.3. SO2 emissions

As presented in Table 5, the SO2 emissions varied as a function of the fuel sulphur content. The lowest and the highest emissions of SO2 were obtained during combustion of Miscanthus (26 mg MJ⁻¹) and wheat bran (227 mg MJ⁻¹) respectively. Corrosion problems might be expected during combustion of wheat bran due to its high sulphur content (above 0.2 wt.% dry basis) [16]. The sulphur conversion rate was not strongly affected by the sulphur content. The lowest and the highest sulphur conversion rates were observed during combustion of vineyard pruning (32%) and wheat bran (73%) respectively.

### Table 5
Sulphur content, SO2 emissions (±SEM) and sulphur conversion rate (±SEM) of the tested fuels. SEM stands for standard error of the mean.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Wheat bran</th>
<th>Hay</th>
<th>Sorghum</th>
<th>Maize</th>
<th>Straw</th>
<th>Miscanthus</th>
<th>Vineyard pruning</th>
<th>Wood with 5% rye flour</th>
</tr>
</thead>
<tbody>
<tr>
<td>S content in the fuel (wt.%) dry basis</td>
<td>0.24</td>
<td>0.13</td>
<td>0.11</td>
<td>0.09</td>
<td>0.10</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>SO2 emissions (mg MJ⁻¹)</td>
<td>220 ± 2.7</td>
<td>75 ± 0.6</td>
<td>70 ± 1.3</td>
<td>58 ± 0.5</td>
<td>44 ± 0.8</td>
<td>26 ± 0.7</td>
<td>7.2 ± 0.9</td>
<td>3.4 ± 0.0</td>
</tr>
<tr>
<td>Sulphur conversion rate (%)</td>
<td>73 ± 0.9</td>
<td>44 ± 0.4</td>
<td>52 ± 1.0</td>
<td>51 ± 0.3</td>
<td>35 ± 0.7</td>
<td>70 ± 1.8</td>
<td>32 ± 1.7</td>
<td>37 ± 0.0</td>
</tr>
</tbody>
</table>

3.3.4. Dust emissions

Fig. 7 shows the dust emissions from the boiler when operated with the tested fuels. In general, with increasing ash content of the biomass fuel also the particle emissions increased considerably [56]. However, no clear correlation was found between the particle emissions and the ash content of the fuels. The emissions from burning hay, wheat bran and Sorghum pellets were lower than expected, given the high ash contents of these fuels. Alkaline metals are key fuel components responsible for the inorganic fraction of the dust emissions. Other relevant species are S, Cl and some heavy metals such as Zn (zinc) [16,31,36]. The high dust emissions observed during straw, maize and wheat bran combustion may be connected to their high contents of alkali metals and sulphur. The high dust emissions from burning straw can also be connected with a high level of products of incomplete combustion given the fact that the CO emissions were high (220 mg MJ⁻¹). Despite the high alkali metals and sulphur contents in wheat bran (275 and 2.4 g kg⁻¹ of fuel respectively), the particle emissions were relatively low (78 mg MJ⁻¹). In comparison to straw, the alkali metals and sulphur contents were approximately 20 and 2 times higher respectively in wheat bran, while the resulting dust emissions were 45% lower. The dust emissions while burning hay were 60% lower than when straw was burned. However, the alkali metals and sulphur contents in the two fuels were very similar. The relatively low dust emissions shown by wheat bran and hay could be explained with the relatively high content of silica. The volatility of potassium was probably significantly reduced by the incorporation into silicate structures [34,35]. The high amount of sintered ash observed during combustion of wheat bran, 40% of slag (Fig. 4) confirms the retention of potassium in the ash.

The emissions while burning agricultural fuels were in general higher than when wood was used. All the fuels tested, with the exception of straw and Sorghum, fulfilled the dust emissions requirement of the FprEN 303-5 [41] for boiler class 3 operated with non-woody fuels (200 mg m⁻³ at 10% O₂ or approximately 133 mg MJ⁻¹). The dust emissions requirements for boiler classes 4 and 5 are respectively 60 and 40 mg m⁻³ at 10% O₂, corresponding to approximately 40 and 27 mg MJ⁻¹. These requirements are only applicable to woody fuels. However, vineyard pruning and Miscanthus fulfilled the dust requirements for both boiler classes. Among the deviations in the dust emission requirements of some of the European countries, it is important to stress the cases of Austria and Germany due to their stricter requirements. In Austria, the dust emissions of boilers with automatic stoking operated with standardised non-woody fuels should not exceed 60 mg MJ⁻¹ and from January 1, 2015 this limit will be lowered to 35 mg MJ⁻¹. According to the current Austrian law, only Miscanthus, vineyard pruning and hay could be burned in the studied boiler. The German deviation only includes emission limits for non-woody biomass fuels to appliances installed after 31.12.2004. From that date on, the dust emissions from boilers with a nominal heat output
between 4 kW and 30 kW and burning e.g. straw and grains, should not exceed 20 mg m\(^{-3}\) at 13% O\(_2\) (approximately 13 mg MJ\(^{-1}\)). Among the agricultural fuels tested, only Miscanthus can fulfil the future emission limits of Austria and Germany in the tested boiler.

3.4. Efficiency

Fig. 8 represents the combustion efficiency of the boiler operated with the tested biomass fuels. The boiler showed efficiencies close to or higher than 90% when operated with agricultural fuels. Boiler efficiency was highest with wheat bran (94%) and Miscanthus pellets (94%) and lowest with Sorghum pellets (89%). The boiler satisfied the minimum efficiency requirements defined in the FprEN 3003-5 [41] with all the fuels tested and was always above the requirements for boiler classes 3, 4 and 5 (74%, 82% and 88% respectively).

4. Conclusions

The technical and environmental performance of a 15 kW pellet boiler fired with different fuels were evaluated.

- Boiler technology:
  - The automatic feeding system and the lambda control were unable to adjust to an optimal level for a broad variety of non-woody biomass fuels.
  - The design of the combustion chamber is not optimal for all the biomass fuels (see Section 3.1.2).
  - Adequate ash management devices were important to enable the boiler to manage fuels with high ash contents.
  - Ash accumulation on the heat exchanger walls rapidly reduced the boiler efficiency.
- It is recommended that boilers for burning agricultural fuels have flexible control systems, automatic cleaning of the heat exchangers and should be adapted to manage high ash content fuels.
- The emissions from burning agricultural fuels were in general higher than when woody biomass was used. Nevertheless, all the agricultural fuels satisfied the legal requirements defined in the FprEN 303-5 with the exception of straw and Sorghum regarding dust emissions.
- Only Miscanthus, vineyard pruning and hay can fulfil Austrian legal requirements of NO\(_x\), and dust emissions (stated in the country deviations of the FprEN 303-5 [41]).

- The boiler showed efficiencies close or higher than 90% with all the agricultural fuels and met the minimum permissible efficiency requirement defined FprEN 303-5 for boiler classes 3–5.

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References


