Experimental investigation on flue gas emissions of a domestic biomass boiler under normal and idle combustion conditions†

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Abstract
Biomass plays an important role in the world primary energy supplies, currently providing ~14% of the world’s primary energy needs and being the fourth largest contributor following coal, oil and natural gas. Over the past decade, domestic biomass heating has received more governmental and public supports than ever before in many developed countries, such as the UK. Although biomass combustion releases some combustion pollutants, biomass is renewable and produces little net CO₂ emissions to the atmosphere. Owing to the low sulphur and low nitrogen contents of many biomass materials, substituting biomass for fossil fuels, particularly coal, can reduce SOₓ and NOₓ emissions. This study investigated flue gas emissions, particularly carbon monoxide and nitrogen oxides, of a domestic biomass boiler under various operating conditions. The biomass boiler used in this study satisfies the current EU regulation (EN 303-05) on emissions of domestic biomass boilers. Emissions of the boiler had been measured not only under normal combustion conditions, but also under ‘idle’ combustion conditions when the boiler was not in but was ready for full operation. The experimental results are analysed and presented in this paper.

Keywords: biomass boiler; wood pellet combustion; flue gas emission

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1 INTRODUCTION

Biomass has been used by human beings for thousands of years because it is a widely available and affordable energy source. Worldwide, currently, biomass ranks fourth as a primary energy source, providing ~14% of the world’s energy needs. In developing countries, biomass accounts for ~35% of the primary energy used. The ever-increasing global energy demand, depleting fossil fuel reserves and global climate change require a further increase in biomass energy utilisation, particularly for distributed electricity generation and domestic heating in both developing and developed countries.

Biomass is C-based organic materials that stem from plants, such as wood, crops and animal wastes. It stores chemical energy from sunlight by photosynthesis in bonds of carbon, hydrogen and oxygen molecules. Biomass energy has its advantage of continuity over the intermittence of solar energy and wind energy. Biomass is renewable and biomass combustion produces no net CO₂ emissions to the atmosphere since biomass absorbs CO₂ during growth and emits the same amount of CO₂ during combustion.

Combustion is the most mature conversion technology used for biomass. Although biomass combustion releases some combustion pollutants (CO, NOₓ, etc.), which need to be controlled [1,2], substituting biomass for fossil fuels, particularly coal, can reduce SOₓ and NOₓ emissions, which are the acid rain precursors, due to the low sulphur and low nitrogen contents of many biomass materials [3]. Combustion of different biomass materials has different characteristics [4,5]. The chemical and physical properties of biomass fuels affect not only the combustion characteristics but also the emissions of various pollutants such as SOₓ, NOₓ, CO and particulates.

Table 1 compares the proximate and ultimate analyses of selected solid biomass fuels and a typical US coal [6]. It can be seen from Table 1 that biomass fuels contain much more
volatiles than coal but they have lower energy densities (i.e. heating values) than coal.

In an ideal case, biomass combustion should represent the complete oxidation of the solid organic part of the biomass into the gases of CO$_2$ and H$_2$O. However, the actual biomass combustion process is far from ideal and involves the formation of pollutants (CO, NO$_x$, etc.) as shown in Figure 1 [7].

This paper presents the results of the experimental investigation on flue gas emissions of a domestic wood pellet boiler under two different combustion conditions.

## 2 EXPERIMENTAL METHODOLOGY

### 2.1 Wood pellet boiler

A UK-manufactured 25 kW$_{th}$ wood pellet boiler (Figure 2a) is used in this study. It satisfies the current EU regulation (EN 303-05) on emissions of domestic biomass boilers and has the capabilities of auto-ignition and automatic control of hot water temperature (Figure 2b). After the hot water temperature is set to a desired value (e.g., 115°C), the boiler automatically starts its ignition and then increases its load to the designed value to heat the water. Once the hot water temperature reaches its set value, the boiler stops fuel feeding and air supply. When the water temperature drops by 2°C below the set value, the boiler will automatically start again—feeding the fuel and supplying the air. The air:fuel ratio was preset at the commissioning stage although it could be adjusted anytime via opening or closing the air damper. Combustion of wood pellets in the furnace is usually very stable (Figure 2c). No visible smoke can be observed from the chimney when in normal operation (Figure 2d) but a bit of smoking can be seen clearly from the chimney when the boiler is in an ‘idle’ state, i.e. the residual fuel is burning in the furnace with no forced air supply in the furnace after the set water temperature is met (Figure 2e).

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### Table 1. Proximate and ultimate analyses of selected solid biomass fuels (dry basis) [6].

<table>
<thead>
<tr>
<th>Name</th>
<th>Fixed carbon (%)</th>
<th>Volatiles (%)</th>
<th>Ash (%)</th>
<th>C (%)</th>
<th>H (%)</th>
<th>O (%)</th>
<th>N (%)</th>
<th>S (%)</th>
<th>HHV (kJ/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Ponderosa pine</td>
<td>17.17</td>
<td>82.54</td>
<td>0.29</td>
<td>49.25</td>
<td>5.99</td>
<td>44.38</td>
<td>0.06</td>
<td>0.03</td>
<td>20.02</td>
</tr>
<tr>
<td>Energy crops Poplar</td>
<td>16.35</td>
<td>82.32</td>
<td>1.33</td>
<td>48.45</td>
<td>5.85</td>
<td>43.89</td>
<td>0.47</td>
<td>0.01</td>
<td>19.38</td>
</tr>
<tr>
<td>Processed wood Plywood Agricultural Wheat straw Coal</td>
<td>15.77</td>
<td>82.14</td>
<td>2.09</td>
<td>48.13</td>
<td>5.87</td>
<td>42.46</td>
<td>1.45</td>
<td>0.00</td>
<td>18.96</td>
</tr>
<tr>
<td>Pittsburgh seam</td>
<td>19.80</td>
<td>71.30</td>
<td>8.90</td>
<td>43.20</td>
<td>5.00</td>
<td>42.18</td>
<td>0.61</td>
<td>0.11</td>
<td>17.51</td>
</tr>
</tbody>
</table>

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**Figure 1. Biomass combustion principle [7].**
Pine wood pellets with a diameter of 6 mm and a length of 5–20 mm were used as the test fuel. Typical fuel analysis is as follows: C 47.5%, H 5.8%, N 0.1%, moisture content 8%, ash content 0.5% (as received), calorific value 17 500 kJ/kg. The fuel consumption rate is ~5 kg/h when the boiler is continuously operating at its design load.

Figure 2. Biomass boiler and its accessories (a) biomass boiler; (b) control panel; (c) flame in the furnace; (d) no visible smoke in normal operation; (e) a bit of smoking when ‘idle’.


2.2 Sampling and measurement of flue gas composition and emissions

In order to measure the flue gas composition and emissions, a stainless water-cooled sampling probe was made and used to sample flue gases at the exit of the boiler, i.e. at the inlet of the chimney after the water heat exchanger of the boiler.

Main composition of the flue gas (CO₂, O₂, CO) was continuously measured by an ABB continuous gas analyser equipped with a non-dispersive infrared (NDIR) gas photometer (Uras26) to measure CO₂ and CO, and an electrochemical cell to measure O₂. A Horiba chemiluminescent NOx analyser connected to a Horiba gas sampling unit was used to measure NOx emissions. The ABB analyser’s NDIR photometer was also capable of measuring NO continuously, and the measured values of NO between the ABB analyser and the Horiba NOx analyser were found to be similar with a difference usually <10 ppmv. The Horiba sampling unit is equipped with a gas-sampling pump which is capable of providing two channels of gas samples for both gas analysers. To protect the gas analysers, quartz wool was placed at the inlet of the probe serving as the first barrier of particles, and a water trap and two further particle filters were also used in the sampling line. Figure 3 shows a schematic of the gas-sampling and analysis system.

Before the flue gas was analysed, the two analysers were calibrated. O₂ was calibrated into 20.9 vol% with fresh air. CO and CO₂ were calibrated with a cylinder of calibration gases purchased from BOC Special Gases (1500 ppmv CO/15.00 vol% CO₂/nitrogen balance), and NOx and NO were calibrated with another cylinder of calibration gases purchased from BOC special gases (150 ppmv nitric oxide/nitrogen balance). If necessary, calibrations of the analysers were repeated during or after the scheduled tests.

3 EXPERIMENTAL RESULTS

3.1 Flue gas composition and emissions

As with many domestic solid fuel combustion devices, the composition and emissions of the flue gas fluctuated because of the fluctuations of fuel feeding rates and combustion air supplies. In addition, fuel feeding of the boiler was not exactly matching the air supply at all times. The boiler fed pellets by means of an auger which rotated at a low speed and intermittently. Fuel feeding and air supply were also running automatically in stop/restart cycles: if the set water temperature was met, they would stop, and restart if the water temperature was 2°C below the set value. The tested pellet boiler was used to drive a micro-scale-combined heat and power (CHP) system with organic Rankine cycle, which is developed by the authors at Nottingham [8]. The CHP system served as a hot water/heat user of the boiler. Therefore, the frequency of the boiler stop/restart cycles depended on the amount of heat extracted by the CHP system. As boiler operated intermittently, the flue gas temperature and other key temperatures of the CHP system fluctuated as shown in Figure 4.

Figure 5 shows the variations of the measured NOx and CO emissions, and CO₂ and O₂ concentrations in the flue gas. It can be seen that the NOx emissions (Figure 5a) follow the same fluctuation trend of CO₂ concentrations in the flue gas, whereas the concentration of O₂ follows the opposite fluctuation trend of CO₂ (Figure 5c). It should be noted that the NOx emissions (expressed in ppmv shown in Figure 5a) were not corrected by the O₂ concentrations in the flue gas. Nitrogen oxides during biomass combustion are mainly due to thermal-NOx mechanism and fuel-NOx mechanism [1], and therefore the more biomass fuel is burnt, the more nitrogen oxides are formed. The fluctuation trend of CO emissions shown in Figure 5b appears to follow the opposite trend of O₂ concentration in the flue gas (Figure 5c).

Figure 5a shows that NOx emissions of the boiler is <90 ppmv all the time, irrespective of normal combustion or idle combustion. In addition, during normal combustion periods, CO emissions of the boiler were found to be ~100 ppmv at the most of the periods (Figure 5b). This confirms that the boiler’s CO and NO emissions satisfy the requirement of the EU regulation (EN 303-5), which only applies to the boiler when it is in normal combustion states. However, there is a significant difference in CO emissions between normal combustion and idle combustion. When the
boiler was in idle states, the CO concentration in the flue gas rose to dangerously high levels—as high as 0.9%, which is about 90 times of the level when the boiler in normal operation periods. If there was insufficient air supply, incomplete combustion and hence high CO emissions would be expected. The peaks of CO shown in Figure 5b corresponded to the moment when the boiler started its idle period following a normal combustion period. When the boiler is in an idle state, there is no forced air supply by the boiler fan but there is residual fuel/char burning in the furnace with the air induced by the natural ventilation via the chimney. Because of limited air supply, high concentrations of CO (Figure 5b) and lower concentrations of O₂ (Figure 5c) were observed during idle periods.

3.2 Quantitative analyses of flue gas emissions

Flue gas emission concentrations were measured by gas analysers. If the flow rate of the flue gas is known, quantitative analyses of the emissions could be done easily. When the biomass boiler is in operation at its design load with a flue gas O₂ concentration of 6%, the dry flue gas flow rate was estimated to be ~550 l (at 15°C and 1 atm)/min. The amount of CO and NOₓ emitted when the boiler is actually in operation could be estimated by using the measured emission concentrations and the estimated dry flue gas flow rate. However, as discussed earlier, the boiler was operating in stop/restart cycles, which means that there were periods when the boiler was idle. When the boiler was in an idle state, there would be neither fuel feeding nor forced air supply but the residual fuel inside the furnace was slowly burning by the use of the naturally ventilated air to the furnace. To calculate the amount of NOₓ and CO emitted by the boiler during the idle periods, the flue gas flow rate is needed.

The flue gas flow rates during the boiler idle periods were expected to be too small to be measured by a common anemometer. In addition, the flue gas temperature was found to be too high for common anemometers. Thus, a flue gas flow rate/velocity calculation approach was first considered. A prevalent calculation formula [9] for stack effect was tried:

\[ Q = KA \sqrt{2g\Delta h \frac{T_i - T_o}{T_i}}, \]  

where \( Q \) is the flue gas flow rate (m³/s), \( K \) is the discharge coefficient (usually taken as 0.65–0.70), \( A \) is the cross-sectional area of chimney (m²), \( g = 9.8 \text{ m²/s} \), \( \Delta h \) is the height of the chimney (m), \( T_i \) is the absolute average temperature of the flue gas (K) and \( T_o \) is the absolute air temperature (K).

The flue gas flow rate found with this approach was ~3000 l/min, much greater than we expected. Formula (1) is suitable only for a chimney with a free open inlet, but the furnace in our case is almost air-tight and the only passage of air to the furnace is via the scroll fan and the connecting pipe. Therefore, the air exchange rate for the furnace should be very small when the fan is not operating.

Eventually, the gas-tracing method [10] was used to measure the flue gas flow rate when the boiler was in idle states. The basic work principle of the gas-tracing principle is the mass conservation law. A tracer gas of a known concentration and a flow rate is injected into the bottom of the chimney, the original flue gases in the chimney are diluted and the measured concentrations of gases before and after the injection of the tracer gases can be used to calculate the flue gas flow:

\[ Q_{\text{flue}}C_{\text{before},i} + Q_{\text{tracer}}C_{\text{tracer},i} = (Q_{\text{flue}} + Q_{\text{tracer}})C_{\text{after},i}, \]  

where \( Q \) is the flow rate and \( C \) is concentration.
The calibration gas – (1500 ppmv CO/15 vol% CO₂/N₂ balance) was used as the tracer gas. The flow rate of the tracer gas used was 60 l (at 15°C and 1 atm)/min.

When the boiler was in an idle state, i.e. after the boiler reached the set water temperature but before restarting, flue gas compositions were measured before and after the injection of 60 l/min of the tracer gas (Figure 6). Using Formula (2) and the data shown in Figure 6, the flue gas flow rate when the boiler was in a idle state was estimated to be \( \sim 93 \pm 5 \) l (at 15°C and 1 atm)/min, which was \( \sim 16\% \) of the flue gas flow when the boiler is in operation at its designed load. Figure 6 shows that both CO₂ and O₂ are good as tracer gas components, whereas

Figure 5. Variations of NOₓ CO emissions and CO₂, O₂ concentrations in the flue gas versus time. (a) NOₓ versus time; (b) CO versus time; (c) CO₂ (triangles) and O₂ (circles) versus time.
CO and NO\textsubscript{x} are less reliable and accurate as tracer gas components. This is mainly because (i) the concentrations of CO and NO\textsubscript{x} before the tracer gas injection were similar to those of the tracer gas; (ii) CO from the tracer gas could be oxidised in the furnace; (iii) NO\textsubscript{x} in the tracer gas could be reduced by the fuel-rich flame in the furnace via the reburning mechanism \cite{11}; (iv) NO\textsubscript{x} formed from the fuel-rich flame in the furnace could be affected by the temperature drop resulted from the tracer gas injection and by CO from the tracer gas.

When the boiler was not in operation and the furnace was at the boiler shade room air temperature, which was slightly higher than the outside ambient air temperature, the tracer gas

Figure 6. Measured concentrations of CO\textsubscript{2}, O\textsubscript{2}, CO and NO\textsubscript{x} in the flue gas before and after the injection of the tracer gas at 60 l/min.
method was also used to find the air ventilation rate. The air ventilation rate was found to be \( \sim 8 \, \text{l/min} \), significantly smaller than the flue gas flow rate when the boiler was in idle state. This proves that the flue gas flow rate determined by the gas tracing method was reliable.

Quantitative estimations of the boiler emissions under both normal combustion and idle combustion conditions can be carried out by the use of the measured CO and NO\(_x\) concentrations (Figure 5a and b) and the estimated flue gas flow rates. The amount of CO emitted during a 3 min idle period was estimated to be as much as twice of that was emitted during a 12 min normal operation period. To reduce the amount of CO emitted during idle periods, the following strategies can be adopted: (i) minimising the duration of idle periods, for example by inserting a large hot water tank between the boiler heat exchanger outlet and the hot water user; (ii) modulating boiler load with the temperature difference between the set point temperature and the actual hot water temperature; (iii) when the boiler is going to be idle, terminating the fuel supply immediately but keeping the boiler air fan on for a further short period.

4 CONCLUSIONS

This paper presents measured flue gas emissions of a domestic biomass boiler under both normal and idle operating conditions. Under normal combustion conditions, the boiler emits low levels of CO and NO\(_x\) which confirms that the boiler satisfies EN 303-5. However, when the boiler was in an idle state, the CO concentration in the flue gas could be dangerously high—up to 0.9%. In order to quantify the amount of CO and NO\(_x\) emitted during the boiler’s idle period, the gas-tracing method was successfully used to determine the flue gas flow rate, which was found to be \( \sim 16\% \) of the flue gas flow when the boiler was in normal operation at its design capacity. The amount of CO emitted during a 3 min idle period was estimated to be as much as twice of that was emitted during a 12 min normal operation period.

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