Analysis of pollutant emissions during circulating fluidized bed combustion of sewage sludge

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Abstract. In this paper, pollutant emissions during air-CFB combustion of sewage sludge, wheat straw, Scots pine and bituminous coal are discussed. Combustion tests were carried out in a bench-scale circulating fluidized-bed reactor. Time-resolved profiles of emitted pollutants (NO, N2O, NO2, SO2 and CO) are presented and analyzed. The effects fuel type on gaseous emissions are evaluated. Due to the high contents of nitrogen, sulphur and ash in sewage sludge high concentrations of NOx, and SO2 may be expected in the flue gas.

1. Introduction

Combustion of sewage sludge derived from the treatment of urban wastewaters is an attractive option to reduce the huge volume of this waste material, minimize odor, and thermally destroy the organic and toxic components [1–5]. However, the low calorific value, the possible generation of pollutants (high contents of sulphur, nitrogen and chlorine) and the complex management of the produced bottom and fly ashes make the pretreatment of the native material a critical issue [6].

There are several commercial technologies available for combustion of sewage sludge. Among them are multiple hearth furnaces, fluidized bed combustors (FBC) and rotary kilns. Fluidized bed combustion has the ability to burn not only coals but also low-quality fuels, biomass and wastes with high contents of ash or moisture. Other advantages of FBC include high combustion efficiency, operational flexibility, low NOx emissions and in situ SO2 capture. Today, FBC is the most popular technology for thermal treatment of municipal and industrial wastes.

Nowadays, only eleven plants in Poland use sewage sludge as fuel therefore further research and development of sewage sludge combustion technology is necessary [7].

Results of experimental research on combustion and co-combustion of sewage sludge in fluidized bed can be found in papers published by Hartman et al., 2005, Shimizu et al., 2007, Urciuolo et al., 2012, Hou et al., 2013, Cammarota et al., 2013 and 2019 and Batistella et al., 2015.

The objective of this study was to investigate pollutant emissions during combustion of pelletized sewage sludge with reference to biomass (wheat straw and Scots pine) and bituminous coal. Combustion tests were carried out in a bench-scale circulating fluidized-bed reactor. Time-resolved profiles of emitted pollutants (NO, N2O, NO2, SO2 and CO) are presented and analyzed.
2. Experimental
Combustion tests were conducted in a 12-kW bench-scale CFB combustor shown schematically in Figure 1. The bench-scale CFBC consists of a combustion chamber (1), a cyclone (2), a downcomer (3) and a loop seal (4). The electrically-heated rectangular combustion chamber (riser), 680×75×35 mm, is the main component of the unit. The front wall of the riser is made of transparent quartz through which the combustion process can be directly observed. Silica sand (particles smaller than 400 μm) to a mass of 0.3 kg constituted the inert bed. The flow rate of air was controlled by valve (16) and measured by rotameter (15). The temperature was held at 850°C by means of microprocessor controllers (11). S-type thermocouples (T1–T3) measured the temperature at three different levels inside the combustion chamber with an accuracy of ±2°C.

For each test, a 0.5-g sample of fuel was dropped into the combustion chamber and burnt in the bed. No sorbent was used to capture SO₂ during experiments. Samples of dry sewage sludge and bituminous coal were in the form of pellets. The methodology of pellet production is described by Kijo-Kleczkowska et al. [14]. Concentrations of NO, NO₂, N₂O, SO₂, CO and other compounds (HCN, NH₃) in the flue gas leaving the combustor were measured on-line by a FTIR spectrometer (Gasmet DX-4000) with sampling frequency of 1 Hz.

The tested material consisted of dry sewage sludge from a large-scale commercial wastewater treatment plant in Poland. Table 1 shows proximate and ultimate analyses of sewage sludge, biomass (wheat straw and Scots pine) and Polish bituminous coal.

Sewage sludge tested in this study had high contents of ash, nitrogen, hydrogen and sulphur in comparison to reference fuels (biomass and coal). The lower heating value of sludge was more than 42% lower than that of coal and approximately 20–30% lower than that of biomass. Due to the high contents of nitrogen, sulphur, volatile matter and ash in sewage sludge high concentrations of NOₓ and SO₂ may be expected in the flue gas.
Table 1. Proximate and ultimate analyses of the tested fuels [14,15].

|                      | Sewage sludge | Wheat straw | Scots pine | Bituminous coal |
|----------------------|---------------|-------------|------------|-----------------|
| **Proximate analysis** (air-dry basis) |               |             |            |                 |
| Volatile matter, wt.% | 51.4          | 68.3        | 76.8       | 26.8            |
| Moisture, wt.%       | 4.9           | 8.4         | 7.0        | 8.7             |
| Ash, wt.%            | 36.4          | 6.1         | 0.6        | 18.9            |
| Fixed carbon \(^a\), wt.% | 7.3          | 17.2        | 15.6       | 45.6            |
| LHV, MJ/kg           | 12.57         | 15.57       | 17.63      | 21.69           |
| **Ultimate analysis** (dry, ash-free basis) |               |             |            |                 |
| Carbon, wt.%         | 52.5          | 50.2        | 50.9       | 73.3            |
| Hydrogen, wt.%       | 6.7           | 5.9         | 5.8        | 4.3             |
| Nitrogen, wt.%       | 7.3           | 0.8         | 0.1        | 1.1             |
| Sulphur, wt.%        | 2.5           | 0.08        | 0.01       | 2.3             |
| Oxygen \(^a\), wt.%  | 31.0          | 43.0        | 43.2       | 19.0            |

\(^a\) by difference.

3. Results and discussion
The time-resolved NO concentrations during combustion of sewage sludge and reference fuels in air-CFB are shown in Figure 2. As expected, NO emission for the combustion of sewage sludge was much higher than those for the combustion of others fuels. This can be attributed to the highest nitrogen content (Table 1) and higher contents of metal oxides such as iron oxides in sewage sludge ash (Fe\(_2\)O\(_3\)=20.6\% [15]). Iron oxides are known to increase conversion of HCN and NH\(_3\) to NO\(_x\). The highest NO emissions were detected during the volatiles combustion for all tested fuels. The lowest instantaneous NO concentrations during devolatilization were measured for bituminous coal what is related to the lowest volatile matter content.

![Figure 2. Instantaneous NO concentrations for sewage sludge and reference fuels.](image-url)
Unexpected, NO emission for the combustion of wheat straw was significantly higher than those for the combustion of coal despite lower nitrogen content. This may be due to the higher temperature of particle due to higher reactivity of biomass [14].

Figure 3 shows the N₂O concentrations during sludge, biomass and coal combustion. The highest N₂O emission (approximately 105 ppm) was detected during the volatiles combustion for sewage sludge while the lowest (below 6 ppm) for woody biomass (Scots pine). The main volatile nitrogen species are NH₃ and HCN. According to Obras-Loscertales et al. [16], when the fuel volatiles are oxidized in the gas phase, HCN is predominantly converted into N₂O, whereas NH₃ is an important source of NO. The instantaneous HCN emissions were below 5 ppm for sewage sludge and 3 ppm for biomass and coal. NH₃ emissions were not detected during air combustion of the tested fuels.

Based on the measurements, it can be concluded that the basic compounds responsible for emissions of N-fuel are NO and N₂O in circulating fluidized bed. NO₂ emissions were not detected during air combustion of the tested fuels.

The time-resolved SO₂ concentrations during combustion of sewage sludge, biomass and coal are shown in Figure 4. The instantaneous emissions of SO₂ for sewage sludge combustion were much higher than those for the combustion of biomass and coal. The highest SO₂ concentrations were detected during the volatiles combustion for sewage sludge (128 ppm), coal (58 ppm) and wheat straw (8 ppm). The SO₂ concentration profile for sludge combustion had a bimodal distribution which may suggest that SO₂ originated from both, organic and inorganic sulphur sources. The lowest SO₂ emissions were measured for biomass due to lower sulphur content (below 0.1%).
Figure 4. Instantaneous SO$_2$ concentrations for sewage sludge and reference fuels.

The CO concentrations in the flue gas during air combustion of the tested fuels are shown in Figure 5. The instantaneous emissions of CO for the combustion of sewage sludge and biomass were much lower than those for the combustion of coal. This can be attributed to the lower carbon content (Table 1). The highest CO emissions were detected during the char combustion for all tested fuels. The highest CO concentrations were approximately 22 ppm and 19 ppm for coal and wheat straw, respectively. The lowest CO concentration was approximately 10 ppm for Scots pine.

Figure 5. Instantaneous CO concentrations for sewage sludge and reference fuels.
4. Conclusions
Pelletized sewage sludge, wheat straw, Scots pine and bituminous coal were combusted in a bench-scale circulating fluidized bed combustor, and the effects of fuel type on emissions of NO, N₂O, NO₂, SO₂ and CO were studied. The main conclusions from this study are as follows:
1. Dry sewage sludge contains much more ash and nitrogen then the reference fuels.
2. Instantaneous emissions of NO, N₂O and SO₂ for the combustion of sewage sludge were much higher than those for the combustion of biomass and bituminous coal.
3. NO₂ and NH₃ emissions were not detected during air combustion of the tested fuels.
4. The SO₂ concentration profile for sewage sludge has a bimodal distribution which may suggest that SO₂ originated from both organic and inorganic sulphur sources.
5. The instantaneous emissions of CO for the combustion of sewage sludge and biomass were much lower than those for the combustion of reference coal. This can be attributed to the lower carbon content.

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