AN INVESTIGATION ON OXY-FUEL COMBUSTION OF SEWAGE SLUDGE IN A 12-KW BENCH-SCALE CFB COMBUSTOR

Monika Kosowska-Golachowska[1*], Aneta Magdziarz[2], Adam Luckos[3], Krzysztof Wolski[1], Agnieszka Kijo-Kleczkowska[1], Tomasz Musiał[1], Damian Richter[1], Katarzyna Środa[1]

[1]*Czestochowa University of Technology, Institute of Thermal Machinery Armii Krajowej 21 42-201 Czestochowa, Poland,*

[2]*AGH University of Science and Technology, Mickiewicza 30 Av., 30-056 Krakow, Poland*

[3]*Sasol Group Technology, 1 Klasie Havenga Road, Sasolburg, PO Box 1, Sasolburg 1947, South Africa*

*Email: *kosowska@imc.pcz.czest.pl*

Abstract – Combustion of sewage sludge samples in air and O_2/CO_2 mixtures with oxygen concentrations in the range from 21% to 40% vol. was conducted at temperature of 850°C in a 12 kW bench-scale CFB combustor. Combustion in air proceeded at ~50˚C higher centre temperatures and was slightly shorter in time compared to combustion in O_2/CO_2 mixture with 21% vol. O_2. Larger heat capacity of CO_2 compared to that of N_2 also retards the ignition of volatiles in O_2/CO_2 mixtures with 21% O_2. However, when the concentration of oxygen in O_2/CO_2 mixtures is larger than 30%, the ignition time decreases and surface and centre temperatures increase significantly with increasing O_2 content.

INTRODUCTION

Increasing production of sewage sludge in Poland has created some environmental problems related to its disposal. These problems have resulted in recent changes in legislation. In the light of the Minister of Economy Regulation of 16 July 2015, regarding the criteria and procedures for releasing wastes for landfilling, the thermal disposal of sewage sludge is important because of its calorific value, which is greater than 6 MJ/kg, and problems associated with its use. Consequently, a restrictive legislation was introduced on the 1st January 2016 for sewage sludge landfilling in Poland (Kijo-Kleczkowska et al., 2016). Sewage sludge incineration is an attractive option because it significantly reduces the volume of the waste material, minimizes odour, and thermally destroys the organic and toxic components of the off pads (Manara et al., 2012, Fytili et al., 2008). Currently, eleven plants in the country use sewage sludge as fuel; thus, this technology must be further developed in Poland (Kijo-Kleczkowska et al., 2016).

Furthermore, greenhouse gases emissions from coal-fired systems, particularly CO_2, become an important issue in the European Union countries. Oxy-fuel combustion is one of the promising technologies for power generation with carbon dioxide capture. This technology can also significantly reduce emissions of NO_x and improve the thermal efficiency of the combustion process through the reduction of flue gas volume by about 80%. In the oxy-fuel combustion, fuel is burnt in a mixture of pure oxygen and recycled flue gas. Because nitrogen is eliminated from the oxidizing gas, the flue gas leaving the combustion chamber is highly enriched in CO_2 which means that the combustion process takes place in an O_2/CO_2 environment. Partial recycling of flue gas helps to control the flame temperature in the combustion chamber (Kosowska-Golachowska et al., 2016). Experimental research on combustion and co-combustion of sewage sludge under different atmospheres can be found in papers by Hanmin et al., 2010 and Zhang et al., 2015. Furthermore, the results of sewage sludge combustion in fluidized bed can be found in papers by Batistella et al., 2015, Cammarota et al., 2013, Urciuolo et al., 2012.

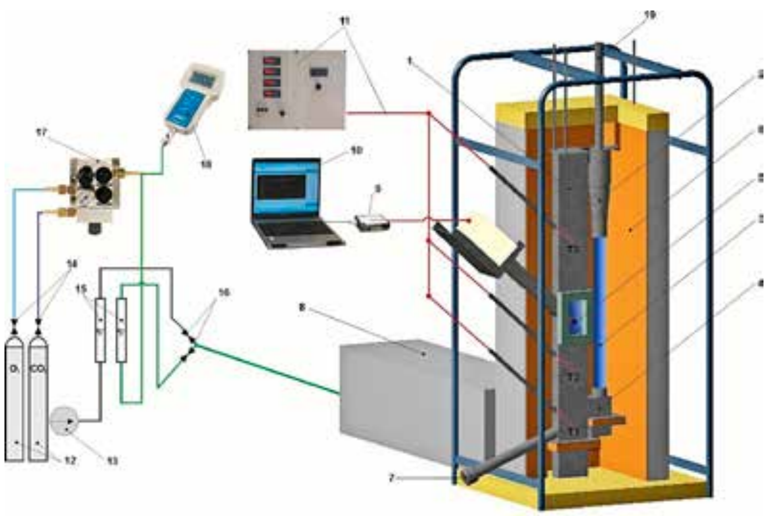
Although sewage sludge combustion is applied in several locations with good efficiency, ash deposition is a new problem, which requires new solutions. Burning sewage sludge generates a large amount of ash containing mineral compounds (more than 30%) creating problems when other fuels are substituted by sewage sludge. Properties of sewage sludge ash can create serious problems because of a high risk of bed agglomeration, slagging and fouling in the combustion devices, which can degrade their performance and severely damage the equipment (Niu et al., 2014, Wang et al., 2012). The presence of ash deposits reduces the heat transfer and combustion efficiency, and damages combustion chambers when large particles break off. The term slagging is used to describe the formation and accumulation of slags on the furnace walls. The reactivity of structural forms of slag and bed agglomeration of depend on the chemical reaction between ash components in particularly silica, alkali, alkaline earth metals and other inorganic compounds present in the environment. The term fouling is used to indicate the formation of ash deposits on heat transfer surfaces in the convective parts of the furnace. It is defined as accumulation of deposits. This term includes accumulation and growth of deposits (ash) on heat exchanger tubing. Fouling causes insulation of the convection tubes and reduces heat transfer. The main elements in the sewage sludge ash are silicon, phosphorus, potassium, calcium, sulphur, chlorine and sodium (Magdziarz et al., 2016). Potassium content is important because it indicates a potential ash fusion and deposition by vaporization and condensation. In renewable fuels combustion K and Cl can be released in gas such as HCl, KCl and potassium exists as potassium silicate, aluminosilicate and sulphate. In the case of sewage sludge, the presence of heavy metals such as Pb, Cd, Cr, Cu, and Ni is a significant problem during the combustion process (Nowak et al., 2013).

The objective of this study was to investigate combustion characteristics of sewage sludge in mixtures of oxygen and carbon dioxide. Results of combustion tests carried out in a circulating fluidized-bed (CFB) bench-scale combustor are reported in this paper.

EXPERIMENTAL

Air and oxy-fuel 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 gases to make up gas mixtures are supplied from cylinders (12) to a mixer (17) and then transferred via a preheater (8) directly into the combustion chamber. Flow rates of gases are controlled by valves (16) and measured by rotameters (15). During combustion tests, the superficial gas velocity was kept at a constant level of about 5 m/s. The temperature was held at 850°C by means of microprocessor regulators (11). S-type thermocouples (T1–T3) measured the temperature at three different levels inside the combustion chamber with an accuracy of ±2°C.



1 - combustion chamber,
2 - cyclone,
3 - downcomer,
4 - loop seal,
5 - fuel sample,
6 - insulation,
7 - drain valve,
8 - preheater,
9 - card,
10 - computer,
11 - temperature measurement and control system,
12 - gas cylinders,
13 - air compressor,
14 - pressure regulators,
15 - rotameters,
16 - valves,
17 - mixer,
18 - gas analyser,
19 - ventilation duct,
T1–T3 - S-type thermocouples

Fig. 1. Schematic diagram of the experimental apparatus for oxy-CFB combustion

A single sewage sludge sample (5) was introduced into the combustion chamber and positioned stationary in the bed. To measure the temperatures in the centre and at the surface of the sewage sludge granule a special stand was constructed. It provides a support for two S-type thermocouples. The tip of the first thermocouple was located inside the particle, while the second thermocouple measured the surface temperature and served as a basket in which the biomass particle was places. The thermocouples were connected via a card (9) to a computer (10) in order to record the temperature measurements. Ignition time and devolatilization time were measured by stopwatch with an accuracy of 0.1s. The intraparticle temperature, the surface temperature, ignition time and devolatilization time were measured simultaneously.

The experiments were carried out in air (base case) and mixtures of O_2/CO_2 with oxygen concentrations in the range from 21% to 40% vol. Video and digital cameras were used to record the progress of combustion.

The tested material consisted of sewage sludge samples in the form of spherical granules. They originated from large-scale commercial sewage treatment plants operating in Poland. Table 1 shows proximate and ultimate analyses of the tested sewage sludge with reference to Polish bituminous coal.

Sewage sludge tested in this study had higher contents of volatiles and ash compared to reference coal. Its carbon content was lower whereas hydrogen content was higher than those in the coal. The lower heating value of sludge was more than 40% lower than that of coal owing to higher ash, oxygen and nitrogen contents. High fuel-N content in the sludge can result in the formation of large quantities of NOx that have to be removed from the off gas in an efficient cleaning system (selective catalytic reduction (SNR) or selective non-catalytic reduction (SNCR)).

Table 1: Proximate and ultimate analyses of sewage sludge and bituminous coal (Kijo-Kleczkowska et al., 2016)

	Sewage sludge	Bituminous coal
Proximate analysis *(air dry basis)*		
Volatiles matter, wt.%	51.4	26.8
Moisture, wt.%	4.9	8.7
Ash, wt.%	36.4	18.9
Fixed carbon (by difference), wt.%	7.3	45.6
Lower heating value (LHV), MJ/kg	12.57	21.69
Ultimate analysis *(dry, ash-free basis)*		
Carbon, wt.%	52.5	73.3
Hydrogen, wt.%	6.7	4.3
Nitrogen, wt.%	7.3	1.1
Sulphur, wt.%	2.5	2.3
Oxygen (by difference) , wt.%	31.1	19.0

RESULTS AND DISCUSSION

Each sewage sludge sample introduced to the combustion chamber undergoes several characteristic stages namely:

- heating and drying,
- ignition and combustion of volatiles,
- combustion of remaining char.

Almost all solid fuels experience these processes but the duration of each process depends on fuel type and its composition (moisture and volatile matter contents, total carbon content), temperature in the combustion chamber, heating rate and oxidizing atmosphere (Kosowska-Golachowska et. al, 2016).

Figure 2 shows pictures of sewage sludge combustion in different oxidizing atmospheres. After heating and drying, the ignition of volatiles follows. Burning volatiles form a distinctive long flame. Differences in combustion times that are related to the composition of oxidizing atmospheres can be noticed. At higher oxygen concentrations, the combustion process is more intense and, therefore, the total combustion time is shorter.

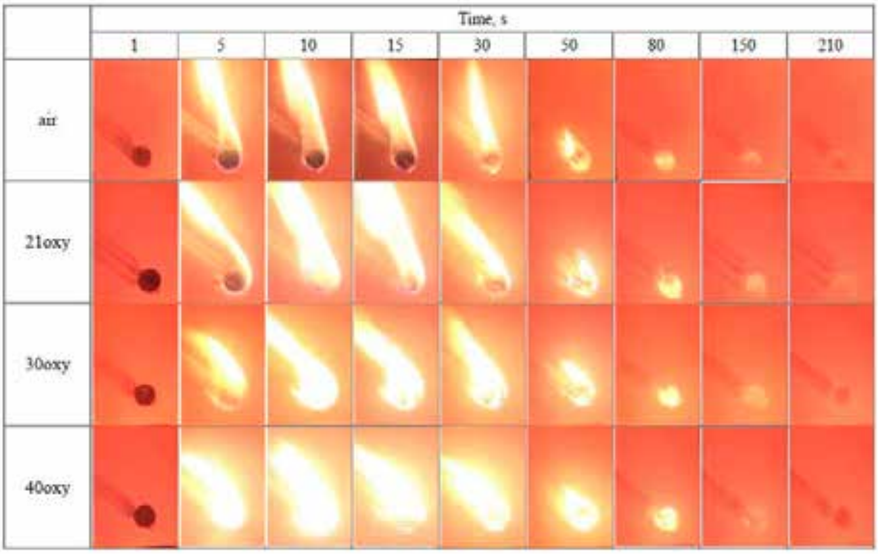


Fig. 2. Combustion of sewage sludge in air and O_2/CO_2 mixtures at 850˚C.

The average ignition time for sewage sludge and bituminous coal in all atmospheres tested is shown in Figure 3. The ignition time at lower oxygen contents (air and 21oxy) is longer for sludge than for coal. However this trend reverses at higher oxygen concentrations (30oxy and 40oxy) and can be related to differences in the devolatilization kinetics and volatile matter contents.

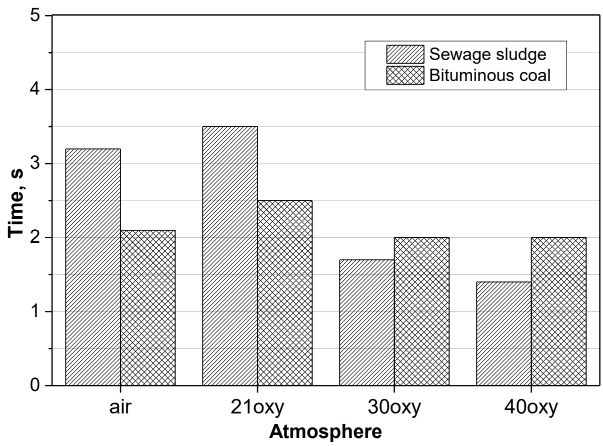


Fig. 3. Average ignition time for sewage sludge and bituminous coal burned in various atmospheres at 850 °C.

Volatile matter combustion times and total combustion times are shown in Figures 4 and 5. The volatile matter combustion time decreases slightly whereas the total combustion time decreases significantly with an increase in oxygen concentration. The total combustion time for sewage sludge in a 40% O_2+60% CO_2 mixture is approximately 45% shorter than that for combustion in air. In all cases, the volatile matter combustion time and total combustion time for sewage sludge are lower than respective values for the reference coal.

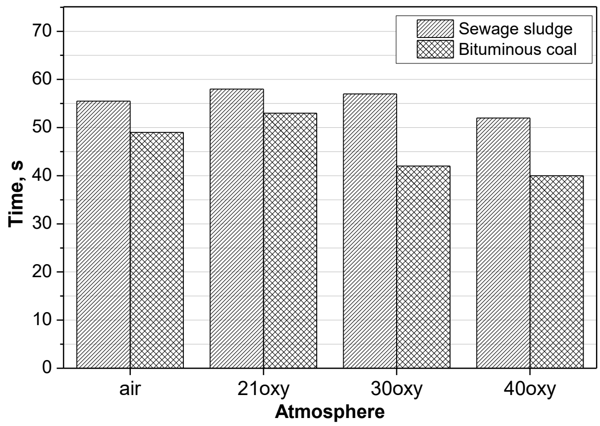


Fig. 4. Average devolatilization time for sewage sludge and bituminous coal burned in various atmospheres at 850 °C.

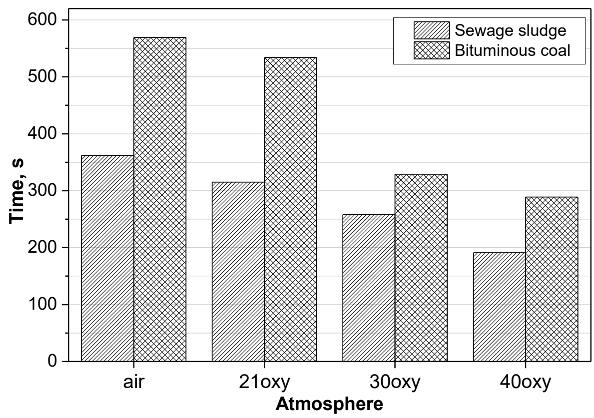


Fig. 5. Average total combustion time for sewage sludge and bituminous coal burned in various atmospheres at 850 °C.

Figure 6 shows temperatures measured at the surface and in the centre of sewage sludge and bituminous coal particles burned at 850˚C in various atmospheres. In all cases, after an initial delay, the centre temperature exceeds the surface temperature and is approximately 100°C higher during the course of combustion. Combustion in air proceeded at slightly higher temperatures and was slightly shorter in time compared to combustion in O_2/CO_2 mixture with 21% vol. O_2.

When the flame approaches its point of extinction, the surface temperature reaches its maximum value. This maximum value varies from ~1100°C, for combustion in air, to ~1210°C for combustion in the mixture of 40% O_2+60% CO_2. In the next stage, i.e. char combustion, the centre temperature was higher than the surface temperature. The maximum centre temperature was slightly higher during combustion in the 40% O_2+60% CO_2 mixture than during combustion in air.

Combustion in an O_2/CO_2 mixture at 21% O_2 resulted in the centre temperature being approximately 40°C lower than that for combustion in air. Higher specific heat capacity of CO_2 lowers the heating rate of the sludge particle. The diffusion coefficient of O_2 in CO_2 is smaller than that in N_2. These two factors influence negatively the kinetics of the combustion process and are responsible for observed decrease in the centre temperature. Graphs shown in Figure 6 can be used to determine, with good accuracy, the total time of combustion. When the char combustion process is completed, the surface temperature and the centre temperature drop to value corresponding to temperature in the combustion chamber.

The surface temperature and the centre temperature are, in all atmospheres tested, lower for sewage sludge than those for the reference coal. These differences can be attributed to higher calorific value of the coal.

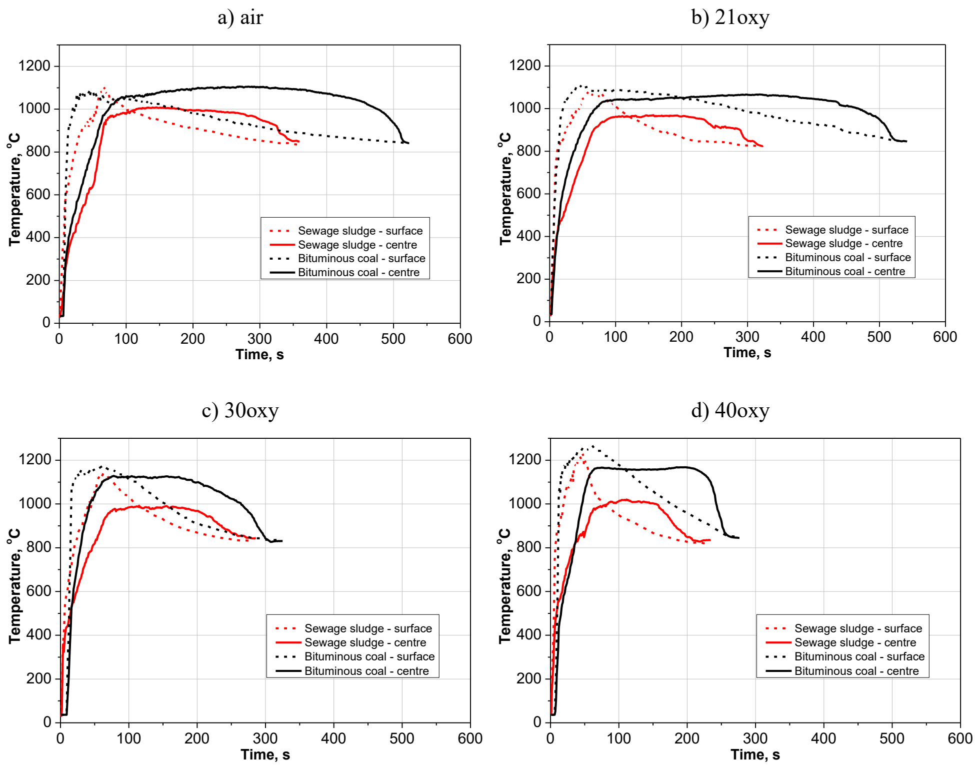


Fig. 6. Temperature profiles for sewage sludge and bituminous coal burned at 850˚C in various atmospheres.

The chemical composition of sewage sludge ashes obtained under air and oxy-fuel combustion are presented in Table 2. The X-ray fluorescence method (XRF, Riau ZSX Primus II instrument) was used to determine the chemical composition. All metal contents are reported as oxides. The main compounds of the ashes are SiO_2, Fe_2O_3, P_2O_5, CaO, Al_2O_3, MgO, TiO_2, K_2O, Na_2O and SO_3. Sewage sludge contains high amounts of phosphorus, calcium and iron as well as silicon. Some minor differences have been observed between ashes obtained under air and oxy-combustion atmospheres. Detailed analysis of sewage sludge ash during air and oxy-fuel combustion in a circulating fluidized-bed can be found in paper by Magdziarz et al. 2016. Similar effect was noticed for the surface morphology. The morphology and surface structure of sewage sludge ash was investigated by SEM method (Scanning Electron Microscopy). Figure 7 shows the morphology of studied ash. The ash consists of fine particles with a variety of shapes. Ash particles are also different in size.

Table 2. Chemical composition of sewage sludge ashes from combustion in CFB in air and O_2/CO_2 mixtures (Magdziarz et al., 2016)

Atmosphere	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	P_2O_5	Na_2O	K_2O	Cl^-
air	26.83	18.12	2.46	20.63	7.13	18.82	0.39	0.83	0.01
21oxy	28.05	17.55	2.35	20.03	6.95	18.31	0.38	0.79	0.03
30oxy	27.48	17.88	2.44	19.95	7.01	18.58	0.39	0.80	0.02
40oxy	28.29	17.56	2.32	20.21	6.89	18.27	0.36	0.81	0.02

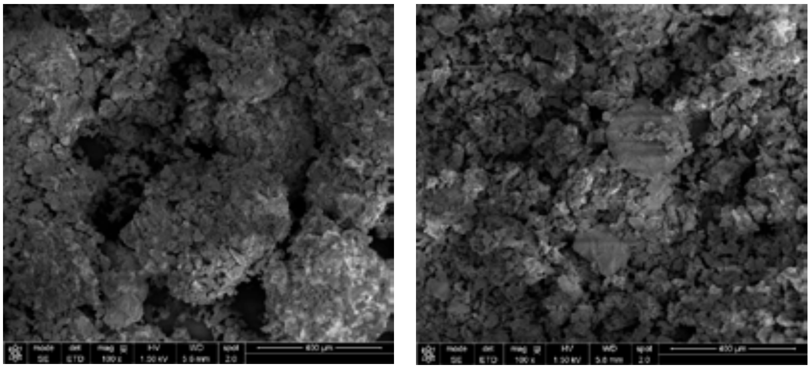


Fig. 7. SEM images of sewage sludge ashes obtained during combustion (air atmosphere) 21%O_2 /79% N_2.

CONCLUSIONS

Chemical analyses and experimental data presented in this study reveal several important differences in the combustion behavior of sewage sludge and coal. Differences in the ignition and combustion times, related to chemical composition of these fuels, can affect design and operation of the boiler or incinerator. Lower temperatures of burning char in the case of sludge may result in lower heat transfer coefficients. Higher slagging and fouling propensity of sewage sludge ash combined with lower heat transfer can create a challenge for the design of heat transfer surfaces. High concentrations of fuel nitrogen in the sewage sludge can increase significantly the concentration of NOx in the off gas. In such a case removal of NOx below the level prescribed by environmental regulations would require the installation of expensive de- NOx systems e.g. SCR or SNCR. One of the biggest risks involved in the incineration of sewage sludge in fluidized-bed systems is the possibility of bed agglomeration due to high concentrations of alkali metals in the ash.

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