Gaseous and Solid Emissions from Combustion of a Bio-solid Waste in Fluidized Bed

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Abstract: The gaseous emissions and the combustion efficiency of a bio-solid waste from a wastewater treatment plant were determined, as a function of excess air ratio and reactor loading, by conducting combustion tests in a bubbling fluidized bed system. Fly and bottom ashes were subjected to mineralogical and chemical analyses. According to the results, the bio-waste studied burned with a uniform temperature along the fluid bed unit. CO, SO_2 and NO_x emissions were below allowable limits, except those of SO_2 at excess air ratio λ=1.5 and those of NO_x at excess air ratio λ=1.3. An increase of excess air from 30% to 50%, or a reduction of the feeding rate from 0.6 to 0.48kg/h resulted in lower SO_2 and NO_x emissions, whereas higher CO emissions. Under test conditions, combustion efficiencies ranged between 98.5 and 98.8%. An improved performance was achieved at a lower reactor loading and a higher excess air ratio. Fly ashes were enriched in Si and P minerals, as well as Cu, Zn and Sr trace metals. All trace element values fulfilled EU legislation for landfill disposal.

Keywords: Ash, Combustion, Emissions, Fluidized bed, Bio-waste.

INTRODUCTION

The amount of sewage sludge generated by wastewater treatment plants across European Union countries is very high (~30kg/per capita/year [1]). To meet European Union Directives, concerning the sustainable management of municipal solid wastes and bio-solids, conversion of these wastes to heat or power seems very attractive, as their volume for land filling is decreased, pathogens and other pollutants are destroyed and there is energy recovery and economic benefits for the communities.

Combustion is currently considered the most suitable process for the implementation of bio-wastes in power systems, contributing also to the net reduction of CO_2 emissions to the atmosphere, due to their biogenic nature. Fluidized bed incinerators are the preferred technology, as they offer increased combustion efficiency with reduced gaseous emissions and no slagging or fouling phenomena owned to ashes [1, 2].

Although several systems burning sewage sludge are already in operation [3], there is limited knowledge on the mechanisms and behaviour of bio-wastes in fluidized bed units [4]. The heterogeneous nature of these wastes requires a careful investigation of their physical and chemical transformations under various operating conditions, which affect the combustion efficiency, the emission of pollutants and the composition of ashes. The latter is important for potential uses or land disposal.

The twofold nature of bio-wastes, a biogenic component associated with an inorganic component, the variable composition unlike other biomass materials, such as the elevated amount of moisture and hazardous species, point to the need for a detailed study of their behaviour in combustion units. Previous investigators focused on the co-firing of sewage sludge with coals in either fluidized bed or pulverized fuel systems [5-7].

Present work aimed at investigating the thermal valorization of a bio-waste from a wastewater treatment plant in the island of Crete, through combustion in a bubbling fluidized bed unit. Axial temperature profiles, combustion efficiency, heat losses and pollutant emissions were measured under different operating conditions, while fly and bottom ashes were subjected to mineralogical and chemical analyses.

MATERIALS AND METHODS

The fuel used in this work was a bio-solid (BS), provided from the wastewater treatment plant of the city of Chania, in Crete. The material, having a high moisture content as received (about 70%), was firstly air-dried and consequently oven-dried to reach a final moisture content of ~1%. For the combustion experiments, the sample was ground in a ball mill and sieved to a particle size of 1-2.8 mm. For fuel characterization, the sample was ground to a particle size <425μm, according to the European standards CEN/TC335.

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E-ISSN: 2311-8741/19

A bubbling fluidized bed system (ID=70mm, H=2m), shown schematically in Figure **1**, was used for the combustion tests. Feeding was performed through one dosimetric silo followed by a silo with a high speed screw feeder, into the inert bed material, about 2cm above the air distributor. Product gas, after passing through a cyclone, a heat exchanger for cooling and a tar collector, was analyzed by a MadurGa-40 plus analyzer. Several K-type thermocouples were measuring the temperature at different reactor heights. The bed material was preheated to ~550°C. Two different feeding rates were chosen for the tests, 0.48kg/h and 0.6kg/h, while excess air varied between 30% and 50%. Agglomeration phenomena were not observed during the tests. Both fly and bottom ashes were collected for mineralogical and chemical analysis.

Mineralogical analysis of crystalline compounds was conducted with an X-ray diffractometer (XRD), model D8 Advance of Bruker AXS, with application of Cu Kα radiation and nickel filter (U=35kV, I=35mA). The XRD scans were performed between 2 and 70 2θ°, with increments of 0.02°/s. A software system DIFFRAC plus Evaluation by Bruker AXS and the JCPDS database were used for data processing and identification of crystalline components. Chemical analysis of ashes in major and trace elements was performed by an inductive coupled plasma mass spectrometer type ICP-MS 7500cx, coupled with an Autosampler Series 3000, both by Agilent Technologies. Phosphorous and silicon measurements were conducted using a spectrophotometer type UV-VIS Hach 4000V and an atomic absorption spectrometer (AAS) Analyst-100 of Perkin Elmer, equipped with a graphite furnace assembly (model HGA 800) and a deuterium arc lamp background correction system. For sample preparation, the procedures of $Li_2B_4O_7$ fusion or acid digestion ($HCl/HF/HNO_3$) were used, depending on the element under determination.

RESULTS AND DISCUSSION

Fuel Characterization

From Table **1**, which represents the proximate and ultimate analyses of the fuel, it can be seen that volatile and ash contents were quite high. Also, the

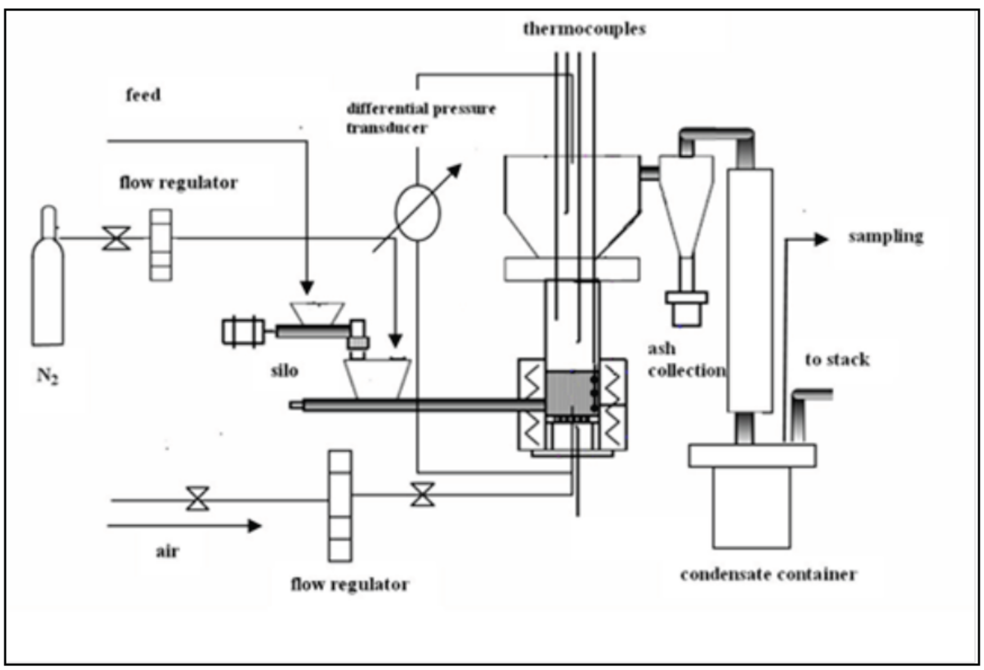

Figure 1: Schematic diagram of fluidized bed system.

Table 1: **Proximate and Ultimate Analysis (% dry weight)**

Sample	Volatile Matter	Fixed Carbon	Ash	C	H	N	O	S	Cl	GCV[a] (MJ/kg)
Bio-waste (BS)	67.2	15.6	17.2	42.4	6.7	8.1	23.9	1.7	0.01	18.8

[a] Gross calorific value.

concentrations of nitrogen and sulphur were high, implying that SO_2 and NO_x emissions during combustion could be elevated and should be taken into consideration. On the other hand, the concentration of chlorine was very low, implying no corrosion effects.

Temperature Profiles Under Various Operating Conditions

The effect of excess air on the temperature profiles along the reactor height is presented in Figure **2**. As clearly shown, for constant feed rate and λ (air ratio), the temperature was quite uniform along the furnace, revealing that volatiles were released at a low rate and burned together with char. Under these conditions, the temperature in the conical part of the system ranged between 384°C and 440°C.

A higher amount of excess air caused some cooling of the flue gas, which resulted in a temperature drop along the furnace up to 52°C. This can be explained by the increased residence time of the fuel inside the bed at lower excess air ratios, which caused a rise in combustion temperature (836°C at λ=1.3).

On the other hand, a higher amount of bio-waste fed into the reactor at an excess air ratio λ=1.3 increased generation of heat by the fuel and consequently its burning temperature, as indicated in Table **2**. However, when excess air was high, 40% or 50 %, flue gas cooling counteracted the higher heat released from the fuel and the axial temperature profile was kept uniform.

Flue Gas Emissions Under Various Operating Conditions

The influence of excess air on the concentration of gaseous emissions (average values ± standard error) is illustrated in Figure **3**. CO emissions were generally low and well below allowable limits [8, 9]. However, when excess air was below 50%, SO_2 emissions of the bio-waste exceeded guidelines [10]. Consequently,

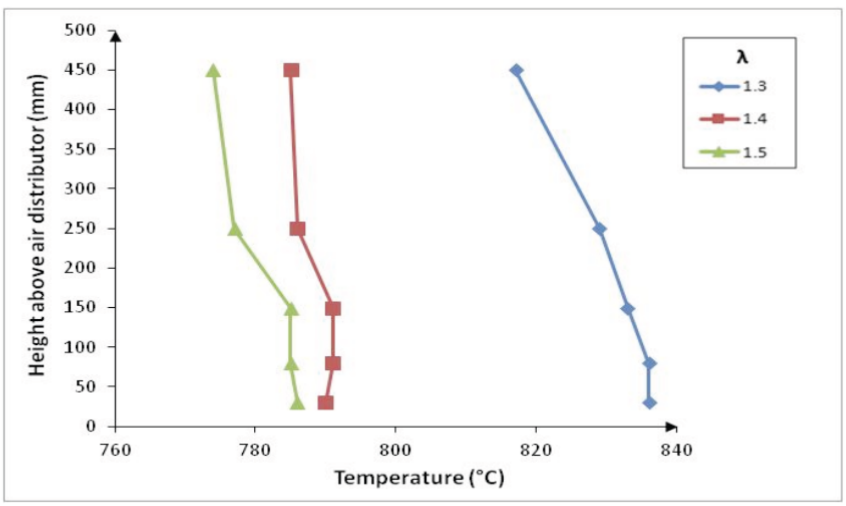

Figure 2: Temperature profiles inside the furnace as a function of air ratio λ at a feeding rate of 0.6kg/h.

Table 2: Fluidized bed Combustion Performance at Different Excess Air Ratios and Feed Rates

Feed Rate (kg/h)	Excess Air Ratio λ	Bed Temperature (°C)	Flue Gas Emissions (ppm_v)			Heat Losses (%)			Efficiency η (%)
			CO	SO_2	NO_x	L_{CO}	L_{ba}	L_{fa}	
0.48	1.3	801-802	1069	263	181	1.17	0.04	0.01	98.8
	1.4	793-794	1151	221.5	139	1.23	0.05	0.02	98.7
	1.5	784-785	1216	166.3	104.9	1.33	0.06	0.02	98.6
0.6	1.3	833-836	1157	268.1	421.3	1.27	0.01	0.02	98.7
	1.4	790-791	1229	247.5	150.7	1.32	0.03	0.03	98.6
	1.5	785-786	1329	108	102.7	1.46	0.04	0.05	98.5

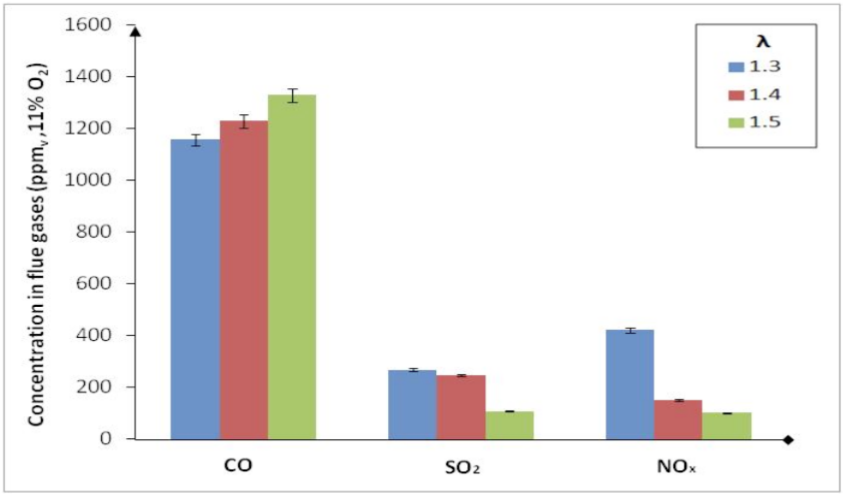

Figure 3: Emissions of pollutant gases at a feeding rate of 0.6kg/h, as a function of air ratio λ.

several measures should be taken in this case, such as use of sulphur absorbent materials within the bed, or flue gas cleaning. Additionally, when excess air was 30% and reaction temperature was higher NO_x levels exceeded legislation limits, so that measures applied either in situ or after production of flue gas are requested.

Furthermore, from Figure **3** it can be observed that when the excess air ratio was raised from 1.3 to 1.5 and the temperature inside the furnace was reduced, CO emissions were increased, while those of SO_2 and NO_x decreased.

The influence of feeding rate on flue gas emissions is shown in Table **2**. An increase in reactor loading from 0.48kg/h to 0.6kg/h resulted in higher SO_2 and NO_x in general, due to the elevated sulphur and nitrogen amount fed with the fuel. Moreover, CO levels were higher, because the increased amount of ash fed with the fuel hindered diffusion of air to the particles and thereby lowered efficiency of combustion.

Combustion Efficiency Under Various Operating Conditions

The combustion efficiencies presented in Table **2** are seen to be high, ranging between 98.5 and 98.8%. These values were kept high, as heat losses owned to the concentration of CO in the freeboard area (L_{CO}) were low, even when reactor loading or excess air ratio were modified. Furthermore, it can be observed that combustion loss deduced from the fly ash (L_{fa}) had the largest portion in the total loss in ash (L_{ba} and L_{fa}). Nevertheless, unburned carbon measured in fly and bottom ashes was so small, that did not practically affect combustion efficiency.

Mineralogical and Chemical Analysis of Ashes

The crystalline mineral phases of fly and bottom ashes, produced at a feed rate of 0.6kg/h and excess air ratio λ=1.4, are listed in Table **3**. Both ashes were dominated by quartz, a great part of which was attributed to the bed material elutriated in the cyclone, together with albite, microcline and muscovite. Phosphorous was incorporated in whitlockite magnesian, while potassium was presented by sulphates or carbonates, in the form of aphthitalite and fairchildite in fly and bottom ashes, respectively. Calcium was identified principally as calcite and in smaller amounts as whitlockite magnesian, srebrodolskite (in fly ash) and fairchildite (in bottom ash). Anhydrite was was concentrated only in the bed material and was formed by dehydration of gypsum ($CaSO_4.2H_2O \rightarrow CaSO_4+H_2O$) and/or reactions between calcium and sulphur liberated during combustion ($CaO + SO_2 + 0.5O_2 \rightarrow CaSO_4$). Furthermore, small amounts of iron were detected in the form of hematite and srebrodolskite.

The chemical analysis of fly ash in major and trace elements is illustrated in Figure **4**. As can be noticed, fly ash contained high proportions of Si and P and lower of Ca and K, which is in agreement with the XRD analysis presented above. Additionally, the levels of Cu, Zn and Sr were elevated, whereas those of Pb and Cr were considerable. The latter was attributed to the operating parameters and furnace configuration, as reported in a previous investigation [11]. The concentrations of heavy metals of great environmental concern, such as As, Hg, Co and Cd, were below detection limits. All measured values were below the

Table 3: Mineralogical Analysis of Ashes

Mineral Phases	Sample		
	Bed Material	Fly Ash	Bottom Ash
Quartz SiO_2	+	++	++
Calcite $CaCO_3$		+	+
Anhydrite $CaSO_4$			+
Albite $NaAlSi_3O_8$		++	+++
Muscovite $KAl_2(Si_3AlO_{10})(OH)_2$	+	+	+
Microcline $KAlSi_3O_8$	+	+	+
Whitlockite magnesian $Ca_{18}Mg_2H_2(PO_4)_{14}$		+	+
Fairchildite $K_2Ca(CO_3)_2$			+
Hematite Fe_2O_3		+	+
Srebrodolskite $Ca_2Fe_2O_5$		+	
Aphthitalite $NaK_3(SO_4)_2$		+	

+++: high intensity ++: medium intensity +: low intensity

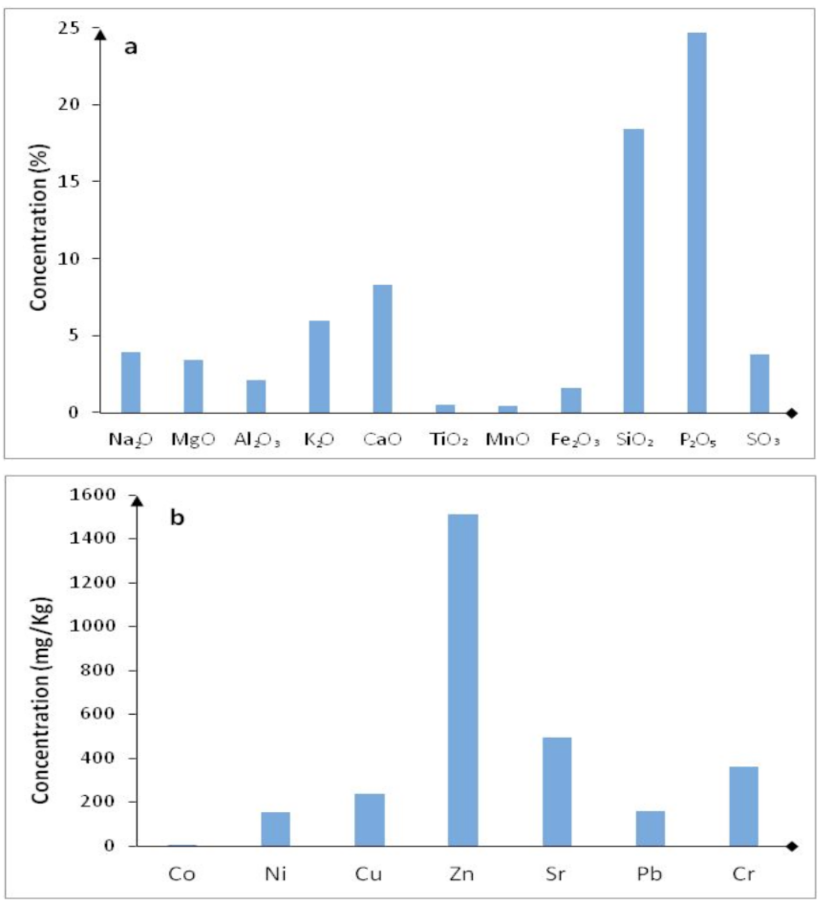

Figure 4: Chemical analysis of fly ash in major (**a**) and trace (**b**) elements.

upper limit for disposal in landfills, according to EU directives [12].

CONCLUSIONS

The bio-waste studied burned with a uniform temperature along the fluidized bed unit. CO, SO_2 and

NO_x emissions were below allowable limits, except those of SO_2 at excess air ratio λ=1.5 and those of NO_x at excess air ratio λ=1.3.

An increase of excess air from 30% to 50%, or a reduction of the feeding rate from 0.6kg/h to 0.48kg/h resulted in lower SO_2 and NO_x emissions, whereas higher CO emissions. Under test conditions, combustion efficiencies ranged between 98.5 and 98.8%. An improved performance was achieved at a lower reactor loading and a higher excess air ratio.

Fly ashes were enriched in Si and P minerals, as well as Cu, Zn and Sr trace metals. All trace element values fulfilled EU legislation for landfill disposal.

ACKNOWLEDGMENTS

The authors kindly thank the laboratories of Hydrocarbons Chemistry and Technology for the ultimate analysis, of Applied Mineralogy for the XRD analysis, as well as of Hydrogeochemical Engineering and Soil Remediation and Inorganic and Organic Geochemistry for the chemical analysis of the ashes.

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Received on 9-10-2019 Accepted on 1-11-2019 Published on 6-11-2019

DOI: https://doi.org/10.12974/2311-8741.2019.07.08