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Principal component analysis of the flue gases exhaust in a functional single chamber incineration system

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ABSTRACT

This plant was designed as a possible option for thermal utilization of rural and urban wastes in Nigeria. Pollutant gases such as carbon monoxide (CO) and nitrogen dioxide (NOx) have numerous health implications when unsafe amounts are released into the atmosphere. Packed-bed technology was installed along with the Wet Scrubber System (WSS) catalyzing the oxidation of packed-bed and pollutant gases. After the water temperature was controlled, the concentration of packed-bed increased resulting in an efficient pollution treatment system. Levels of pollutant gas emission were found to be beneath National Guidelines for Emissions. Data were collected from the experiments conducted in the Centre for Industrial Studies (CIS) workshop, Department of Mechanical Engineering, Abubakar Tafawa Balewa University, Bauchi, Bauchi State, Nigeria, which were analyzed and examined. Determination of the heat contents were carried out using two methods: IMR 1400 Gas Analyzer PL model and Dulong's formula. Some samples of the wastes were analyzed with IMR 1400 Gas Analyzer PL model in the above named Centre. This is important because it is a direct measure of the temperature requirements that the specific waste was place on the system. The comparison of the net enthalpy values for textile, paper and wood wastes blended with plastic at different compounding ratios used which shows that 25%PL + 75%TE had the enthalpy calorific values of 8.077 MJ/mol, 10.287 MJ/mol, 10.241 MJ/mol and 11.045 MJ/mol for CO, CO_2, NO_X and SO_X and 100%PA had the lowest value of 2.974 MJ/mol, 3.788 MJ/mol, 3.771 MJ/mol and 4.067 MJ/mol for CO, CO_2, NO_X and SO_X respectively. The maximum temperature of the furnace attained from the energy balance based on this value around the combustion chamber was 277 K.

Keywords: Solid-waste, steam, temperature, flue gases, calorific value, energy, combustion.

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INTRODUCTION

In most cities in the developing world, several tons of municipal solid waste is left uncollected on the streets each day, interfering with the free flow of drainage, creating a feeding ground for pests that spread diseases and creating an enormous health and infrastructural problems (Ferronato and Torretta, 2019). The degradation of the environment caused by inefficient disposal of waste can be expressed by the contamination of soil, surface and groundwater through leachate; the spreading of diseases by different vectors like birds, insects and rodents (Gangola et al., 2018). Similarly, to reduce landfills, some countries have successfully implemented new strategies, focusing on waste to energy, using incineration and advanced thermal treatment where these researchers are providing treatment units for the flue gas to reduce dioxins released

to the environment (Makarichi et al., 2018).

The energy demand has been on the increase mostly attributed to the growth in the human population as well as a significant rise in the commercial and industrial activities witnessed across the globe. Fossil fuels such as petroleum products, coal, natural gas, etc., are the most important energy sources, which supply about 80% of the global primary energy requirement (Sansaniwal et al., 2017). The depletion of fossil fuel, which is non-renewable, has been a global issue; nevertheless, it is the growing utilization that is currently presenting a new and major challenge. According to Tursi (2019), the increasing usage of fossil fuels for industrial and post-industrial development has attracted growth in wealth, but so also higher levels of pollution and the consequent degeneration of public health. In 2018, the global carbon dioxide (CO) emissions from fuel combustion reached 32.8 billion tonnes (IEA. 2019). The rise of carbon dioxide concentrations will continue unless emissions are drastically reduced. A recent report noted that the earth is set to warm up to 3.2 ºC by 2100 unless efforts to cut emissions are tripled (UNEP, 2019). The desire for the average rise in temperature to be sustained well below 2°C requires total decarbonization of energy generation away from fossil fuels (Watts et al., 2018). Interestingly, fossil fuels are not the only constituents of environmental degradation. Inefficient use and disposal of biomass as well as inadequate proper cooking technologies also persist. Anenberg et al. (2013) reported that 3 billion people rely on fuelwood, coal, charcoal, or animal waste for cooking and heating. Most of these people are predominantly found in developing countries. They get exposed to high indoor concentrations of health-damaging pollutants including particulate matter and carbon monoxide due to incomplete combustion.

The challenges of urban solid waste management can be addressed by building an incinerator to thermally treat the solid waste as a part of the integrated waste management method. The significant volume and weight reduction, and the energy potential, have made incineration of MSW an attractive alternative. The incineration of solid waste reduces the waste to about 10 to 15 % of its original volume, destroys all the harmful substances contained in the waste, and so it is very ideal in big cities where the availability of land is very scarce (Makarichi et al., 2018). The equipment can also be incorporated with a heat recovery device to produce steam for process industries and power plants. The process of incineration involves taking into consideration the temperature, the combusting gases reach, the length of time the gases remain at elevated temperatures, how well the air and the gases are mixed and whether there is adequate oxygen to permit complete combustion (Niessen, 2014). The incineration of solid waste is imperative in a situation whereby the waste is so degraded to such an extent that recycling is no longer cost-effective.

Advanced energy-from-waste technologies

The characteristics of advanced thermochemical processes are based on cutting-edge technologies.

Two-stage gasification and plasma process

The two-stage gasification and plasma process can treat different waste feedstocks to produce electricity, steam and a vitrified product. The core of the system is the two-stage process of treating the waste by gasification followed by plasma cleaning to produce a low impurity, high energy syngas with high carbon conversion efficiencies (Ramos et al., 2019). Four main sections are identified: solid fuel preparation unit; syngas generator unit; syngas refining unit; and power production unit. In the solid fuel preparation unit, the received waste is pretreated and transformed to RDF by shredding and drying (Cai et al., 2021).

In the syngas generator unit, the waste is thermally decomposed in a bubbling fluidised bed gasifier and transformed into a high-temperature raw syngas. Oxygen and steam are used as oxidizing agents; the oxygen is assumed to be supplied by a cryogenic air separation process (Mazzoni and Janajreh, 2017). The flows of the oxidizing agents are controlled to maintain the bed temperature and the required syngas quality and an inert gas (nitrogen) are supplied to the gasifier as a purge. Two main streams are distinguished going from the gasifier to the plasma converter: raw syngas and ash (Cai et al., 2021). The raw gas produced in the gasifier still contains entrained ash particles, unconverted char and residual tars and therefore further processing is required in the plasma converter. This unit produces high purity syngas due to the cracking of the tars exposed to the high plasma temperature (Khiari et al., 2019). Particles entrained in the gas are captured in the plasma converter and, together with the ash coming from the gasifier. Unlike common incineration plants that produce bottom ash and fly ash which must be treated before use or disposal, this vitrified product is stabilized and can be used directly as an aggregate in road construction, without further reprocessing. In the syngas refining section, the syngas is cooled and cleaned (Sun et al., 2021).

The finest ash still contained in the syngas is collected and removed in the dry filter and in the scrubbers where APC residues are produced. Further cooling is achieved in the quench and water scrubbing systems (such as acid and alkali scrubbers) used to remove contaminant compounds, i.e. phenol, sulphur dioxide, hydrogen sulphide and ammonia (Tong et al., 2018). Effluents from the quench and scrubber units are treated in standard wastewater treatment plants. Finally, the last section includes the generation of electricity using a gas engine and cleaning of the flue gas. The steam produced by

cooling the flue gas is fed to a steam turbine to produce power (Tong et al., 2018).

Two-stage fast pyrolysis and combustion process

Fast pyrolysis combustion process is a two-stage process, deploying a pyrolyser and a combustor Pyrolysis application to waste for energy recovery is limited to a few specific waste flows. In particular, pure and homogeneous waste streams are required to produce good quality oil, which can be used in highly efficient energy conversion devices (Vienescu, 2018). The pyrolyser converts the waste in the syngas generator unit using an internally circulating fluidized bed; the char produced by pyrolysis is converted in the bubbling fluidized bed combustor. After cooling and partial dust removal by a cyclone, the remaining dust is removed from the syngas by multistage scrubbing with hydrocarbons scrubbing oil (Zaman et al., 2017).

Two-stage gasification and syngas combustion process

The gasification syngas combustor process uses a moving grate gasifier to produce a synthesis gas which is then oxidized at a high temperature in a secondary chamber. The system incorporates a dry flue-gas cleaning system, which involves the injection of lime and activated carbon (Anukam et al., 2016). Hot gas from the secondary chamber is recovered for steam production and a steam turbine is then used to produce electricity. Bottom ash produced in the gasifier as well as APC residues from the flue-gas cleaning system is treated and sent to a landfill (Evangelisti et al., 2015).

MATERIALS AND METHODS

Materials

Dimensioning of incinerator

The incinerator was designed to treat a bulk waste of 3 kg for every sample of the experiment. Using the bulk density of municipal solid waste ranging from 760.05 to 920.12 kg/m^3 (Bowan and Tierobaar, 2014), the volume of the solid waste in the incinerator for batch treatment is 0.54 m^3. Consequently, the total volume for the thermal treatment is 3 times the batch volume (treatment chamber}, thus, 1.62 m^3.

A heat recovery unit was also included in the design via a heat exchanger to determine the energy using the thermocouple, pressure gauge and valve. To reduce the effect of lost heat on operators of the incinerator, the unit is encased with the 5 mm plates forming a dimension of 663.43 mm (height) × 635 mm (width) × 635 mm (length). On the flue gas, the treatment unit is mounted on a 3” exhaust pipe.

Figures 1 and 2 show the detailed drawing of the pictorial view of the installed incinerator and the pictorial view of the scrubber.

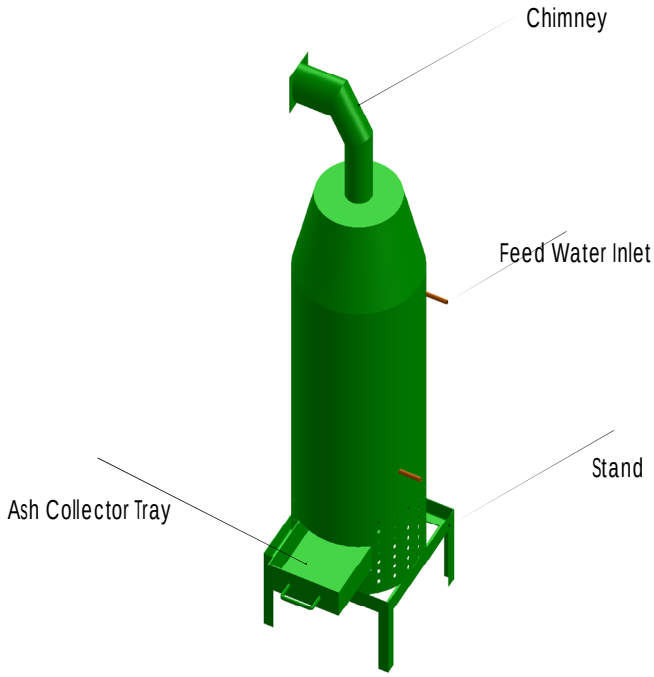

Figure 1. Pictorial view of installed incinerator.

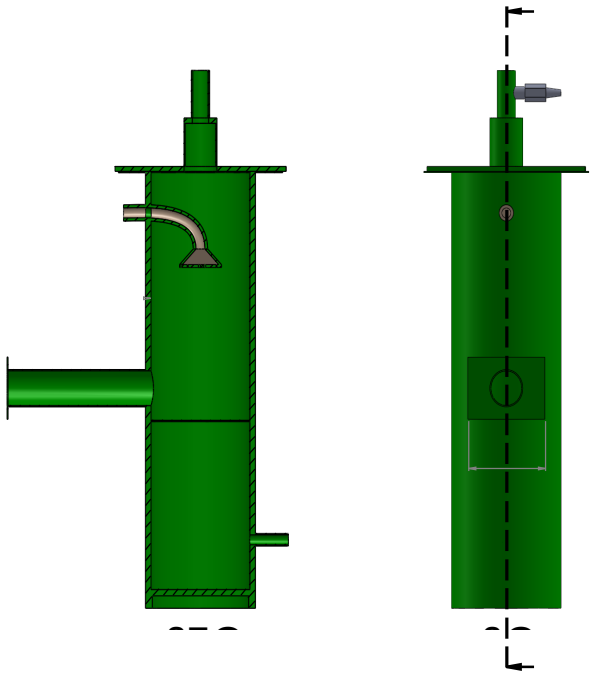

Figure 2. Pictorial view of the scrubber.

Design concept of packed bed wet scrubber

A vertical design concept is considered for the packed bed wet scrubber, the liquor is sprayed from the top and flows down across the bed. Appropriate distribution of liquor is important for the efficient removal of gases (Olanrewaju and Fasinmirin, 2019). The collection of acid gases in packed-bed scrubbers is achieved by absorption. The effectiveness of absorption in packed beds is related to the uniformity of the gas velocity distribution, the surface area of the packing material, the amount and uniform distribution of scrubber liquid, and the pH and turbidity of the scrubbing liquid. The measure of gas absorption is affected by the extensive liquid surface contacted by the gas stream as the liquid flows downward over the packing material. A variety of available packing materials offer a large exposed surface area to facilitate contact with and absorption of the acid gases.

The packing materials which range in size from 0.5 to 3 inches are randomly oriented in the bed. Typically, sodium hydroxide (NaOH) or occasionally sodium carbonate (Na_2CO_3) with water neutralizes the absorbed acid gases in a packed-bed scrubber. These two soluble alkali materials are preferred because they minimize the possibility of scale formation in the nozzles, pump, and piping. For the typical case of using NaOH as the neutralizing agent, the HC1 and SO collected in the scrubber react with NaOH to produce sodium chloride (NaCl) and sodium sulphite (Na_2SO_3) in an aqueous solution.

Experimental methodology

Temperature dependence of the heat capacity

Evaluation of the integral requires knowledge of the temperature dependence of the heat capacity. This is usually given by an empirical equation; the two simplest expressions of practical value are:

$$\frac{C_P}{R} = \propto + \beta T + \gamma T^2 \quad (1)$$

and

$$\frac{C_P}{R} = a + bT + CT^2 \quad (2)$$

Where α, β, and γ and a, b, and c are constants characteristic of the particular substance. Except for the last term, these equations are of the same form. We, therefore, combine them to provide a single expression:

$$\frac{C_P}{R} = A + BT + CT^2 + DT^{-2} \quad (3)$$

Where either C or D is usually zero, depending on the substance considered. Because the ratio CP/R is dimensionless, the units of CP are governed by the choice of R. The parameters are independent of temperature, but, at least in principle, depend on the value of the constant pressure. However, for liquids and solids, the effect of pressure is usually very small.

Heat capacity, C is an extensive property while the corresponding intensive property is the specific heat capacity, c which is found by dividing the heat capacity of an object by its mass. Dividing the heat capacity by the amount of substance in moles yields its molar heat capacity.

Specific heat capacity, $c = \frac{A+BT+CT^2+DT^{-2}}{M}$ (4)

Equations 1 and 3 were substituted into the equation of enthalpy of the reaction below:

$$\Delta H = m \times s \times \Delta T$$

Which gives
Enthalpy,

$$\Delta H = (A + BT + CT^2 + DT^{-2})R\Delta T \quad (5)$$

Where, R = 8.314 J/mol/K (constant value applicable to all the flue gas composition on the values of the Universal Gas Constant table)

$\Delta H = A + BT + CT^2 + DT^{-2}$ (Constants in equation C_P on Heat Capacities of Gases in the Ideal – Gas State table) as attached in the Appendix.

$$\Delta T = T_2 - T_1$$

where T_2 = Flue gas temperature
and T_1 = Ambient temperature (28°C).

Dulong-Berthelot model equation

The Dulong-Berthelot model was utilized in determining the heating value of biomass. This modified form was expressed as:

$$GVC\left(\frac{MJ}{kg}\right) = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1ASH$$

Flue gas analyzer unit (IMR 1400)

A flue gas analyzer is a device that measures the

emissions and efficiency of flue gases. The gas analyzer is a device that measures emissions straight from the combustion chamber. Flue gas emission tests (CO, CO_2, NOx and SO_X) were carried out under natural induced airflow at the exit of the boiler. The analyzer is available in a variety of models; however, in this study, the IMR 1400 PL model was used. Figure 3 is a diagram of the gas analyzer used.

Figure 3. Diagram of IMR 1400 Gas Analyzer PL model.

Unit of measurement

The arrow selector must be in front of parts per million ('ppm') and then the 'menu' button pressed to show all the toxic sensor values in ppm. The IMR® 1400 shows ppm as 'p'. The Engineering unit selection CO, CO_2, NO_X and SO_X values can be shown as

- ppm - mg/m^3
- mg/kWh
- mg/Ref.(O_2).

But, in this work, CO, CO_2, NO_X and SO_X are measured in ppm and the default setting is ppm.

The carbon monoxide (CO), NOx, SOx, and carbon dioxide (CO_2) parameters are measured and calculated by the gas analyzer before and after the scrubber.

The gas analyzer was started and allowed to idle before being set to 1200 revolutions per minute. The duct was then connected to the analyzer via the gas sampling probe. During the zero calibration, the gas sampling probe was initially at ambient air, and the unit was turned on to begin the zero calibration, which took 3 minutes before measurement began. The selection menu on the display screen was used to select the fuel type and engineering unit (ppm). The exhaust duct valve was opened, and readings were taken at the point source and 3 meters measured distance for each set of experiments. A five-minute interval was observed before the next reading was taken, and after each run, the dust filter and sensor were removed and cleaned free of soot, and readings were recorded.

RESULTS AND DISCUSSION

Enthalpy of CO, CO_2, NO_X and SO_X from Plastic, with different compounding ratios of plastic and textile, plastic and paper, and plastic and wood

Table 1 shows the enthalpy while Table 2 presents the composition of the flue gases in relation to the total environmental impacts. For the pyrolysis, the major gaseous products for this research work were CO, CO_2, NOx, and SOx. It is worth noting here that the emission of these gases represents a contribution to the hazardous impact on the environment. As shown in Table 1, CO gas was the most abundant in the materials when compared to CO_2, NOx, and SOx.

Flue gas analysis

The characteristics of CO, CO_2, NOx, and SOx formation were investigated using data from the furnace outlet to the scrubber inlet. Table 2 shows the final emission results in flue gas before and after the scrubber. The flue gas emission tests were carried out under natural induced airflow at the exit of the boiler. The details of the

Table 1. Enthalpy of CO, CO_2, NO_X and SO_X from plastic, textile, paper and wood in different compounding ratios.

S/No	Samples	Enthalpy (MJ/mol)				Change in Tempt, ΔT (K)
		CO	CO_2	NO_X	SO_X	
1	100%PL	4.082	5.199	5.176	5.582	140
2	75%PL + 25%TE	5.161	6.574	6.544	7.058	177
3	50%PL + 50%TE	7.523	9.582	9.539	10.288	258
4	25%PL + 75%TE	8.077	10.287	10.241	11.045	277
5	100%TE	5.365	6.834	6.803	7.337	184
6	100%PA	2.974	3.788	3.771	4.067	102
7	75%PA + 25%PL	4.432	5.645	5.620	6.061	152
8	50%PA + 50%PL	5.452	6.945	6.914	7.456	187
9	25%PA + 75%PL	5.890	7.502	7.468	8.055	202
10	100%WO	6.473	8.245	8.208	8.852	222
11	75%WO + 25%PL	5.365	6.834	6.803	7.337	182
12	50%WO + 50%PL	4.519	5.756	5.731	6.180	155
13	25%WO + 75%PL	3.266	4.160	4.141	4.466	112

Table 2. Composition of the flue gas.

S/No	Samples	Flue gases before scrubber (%) ppm				Temperature, T (ºC)	Flue gases after scrubber (%) ppm				Temperature, T (ºC)
		CO	CO_2	NO_X	SO_X		CO	CO_2	NO_X	SO_X	
1	100%PL	320	50	150	224	168	108	7	21	13	105
2	75%PL + 25%TE	338	63	168	315	205	176	12	34	40	134
3	50%PL + 50%TE	340	70	175	351	286	180	25	38	52	170
4	25%PL + 75%TE	362	78	184	356	305	190	27	47	58	185
5	100%TE	330	67	90	230	212	115	3	23	85	128
6	100%PA	210	41	6	108	130	98	15	00	3	100
7	75%PA + 25%PL	264	51	13	140	180	109	19	2	9	145
8	50%PA + 50%PL	291	70	16	175	215	138	21	4	25	190
9	25%PA + 75%PL	320	79	21	206	230	160	35	5	28	201
10	100%WO	450	85	10	90	250	170	61	1	63	175
11	75%WO + 25%PL	426	81	17	137	210	152	40	3	80	140
12	50%WO + 50%PL	382	72	25	215	183	103	25	16	130	108
13	25%WO + 75%PL	360	61	29	240	140	90	15	18	142	95

measurement system were introduced elsewhere (Chen et al., 2010).

Before the scrubber, the concentrations of flue gases at the furnace outlet were higher. The temperature at the sampling ratio was the primary factor influencing the concentrations of the various gases. Also, too little air was supplied to the burner, and the oxygen is not enough to completely form CO_2 with all the carbon in the fuel. Instead, some oxygen combines with carbon to form carbon monoxide (CO). CO is a highly toxic gas associated with incomplete combustion and efforts must be made to minimize its formation. This effort goes hand-in-hand with improving fuel efficiency and reducing soot generation. As is well known, gases can be generated directly from waste as well as in the combustion system via the homogeneous (same sample) and heterogeneous (different samples) pathways (different compositions of samples). (Figures 4 to 9)

CONCLUSION

The characteristics of CO, CO_2, NOx, and SOx formation were studied using data from the furnace outlet to the scrubber inlet, and the results show the final emission results in flue gas before and after the scrubber. Before the scrubber, flue gas concentrations at the furnace outlet were higher. The primary factor influencing the concentrations of the various gases was the temperature at the sampling ratio. During the high-temperature

incineration of pure plastic waste, most gases were released. The amounts of gases released in the heterogeneous samples are proportional to the amount of compounded plastic material, indicating that the more plastic there is, the more flue gases are released, and the scrubber was critical in reducing CO, CO_2, NOx, and SOx emissions.

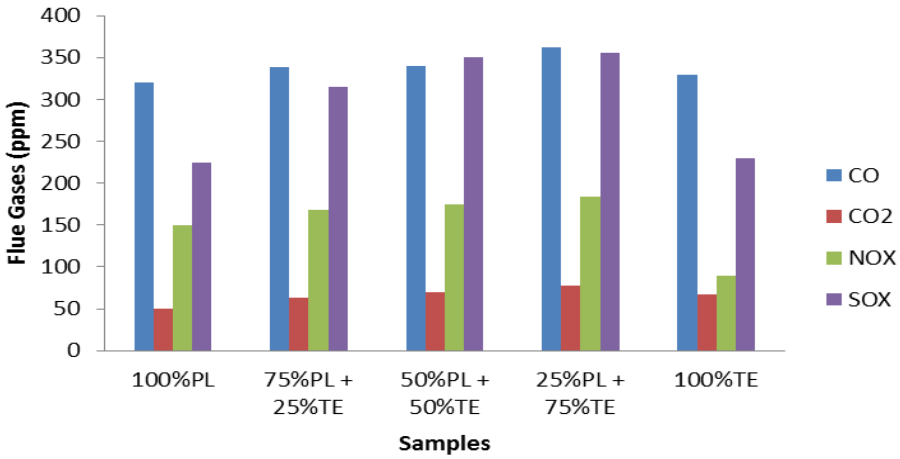

Figure 4. Flue gases before scrubber for plastic, textile and textile/plastic blends.

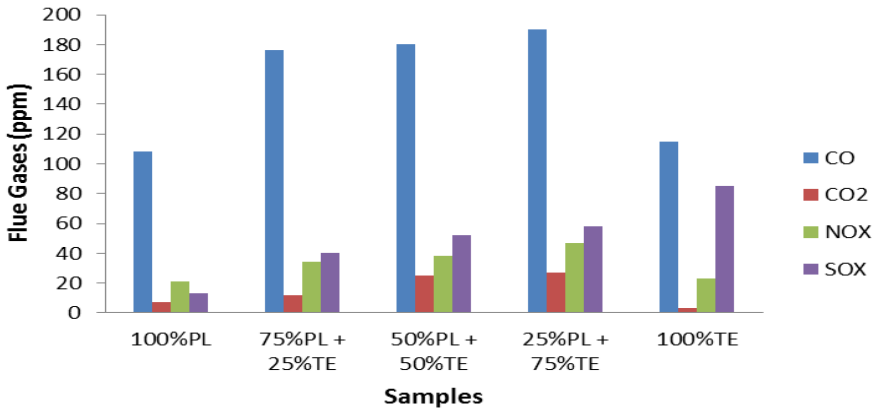

Figure 5. Flue gases after scrubber for plastic, textile and textile/plastic blends.

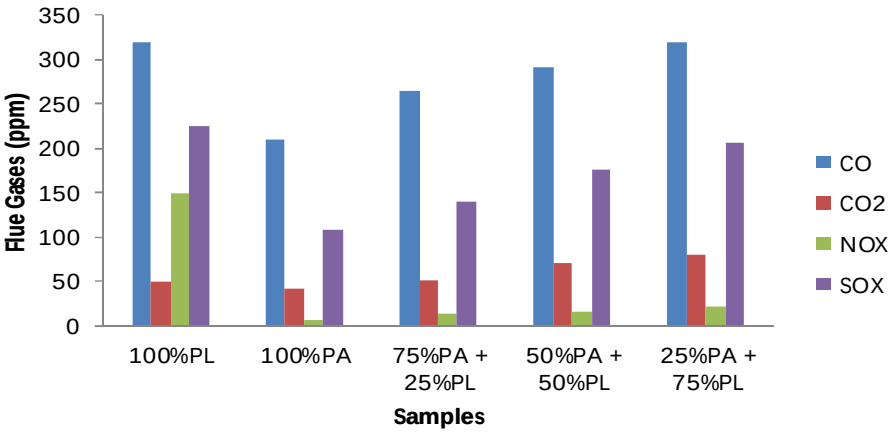

Figure 6. Flue gases before scrubber for plastic, paper and paper/plastic blends.

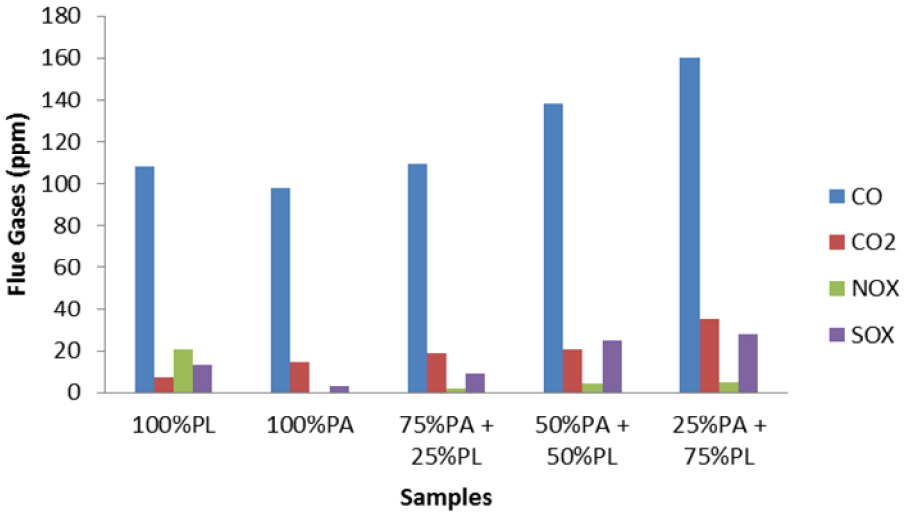

Figure 7. Flue gases after scrubber for plastic, paper and paper/plastic blends.

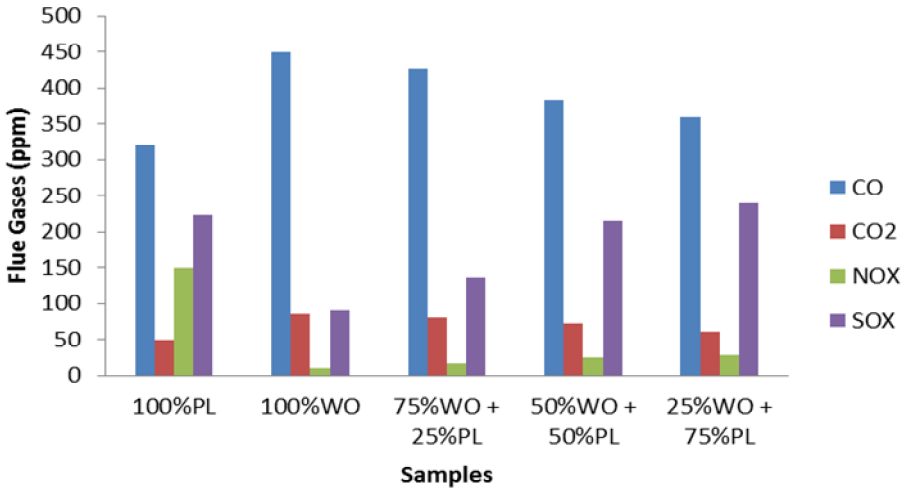

Figure 8. Flue gases before scrubber for plastic, wood and wood/plastic blends.

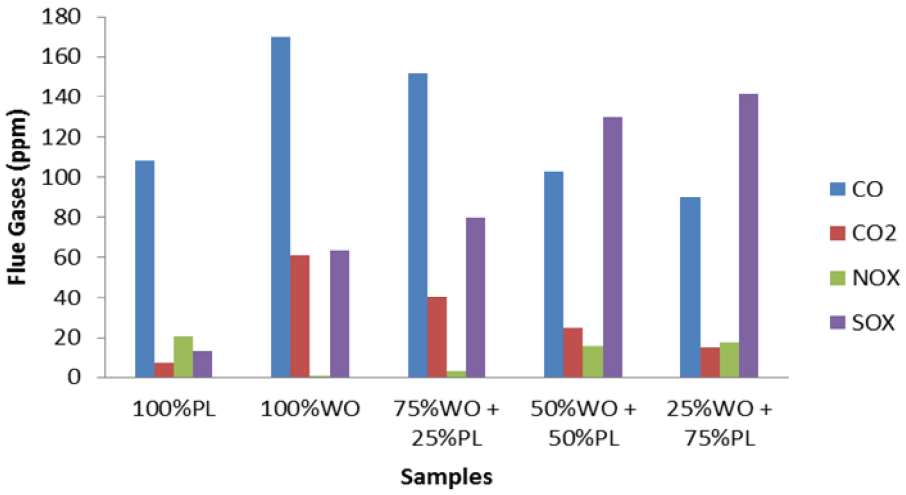

Figure 9. Flue gases after scrubber for plastic, wood and wood/plastic blends.

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