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# Combustible Gaseous Products from Pyrolysis of Combustible Fractions of Municipal Solid Waste

\*Buah, W. K. and Williams, P. T.

## **Abstract**

Municipal Solid Waste (MSW) sample was pyrolysed under inert atmosphere of nitrogen in a static bed pyrolysis reactor, heated at a controlled rate of  $10\text{ }^{\circ}\text{C min}^{-1}$  to a final temperature of  $700\text{ }^{\circ}\text{C}$  to recover combustible gaseous product. The yield of the combustible gaseous product was 23.01 wt%. Other pyrolysis products were 32.00 wt% char and 44.99 wt% oil. The combustible gaseous product evolved, analysed off line by gas chromatography to contain mainly  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2$ ,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$  and  $\text{C}_3\text{H}_8$  has relatively high calorific value of  $18.0\text{ MJ m}^{-3}$ , making the gas suitable for use as a fuel. The significance of this research is that the pyrolysis recovered combustible gas can now be stored conveniently and easily transported for various applications. This research, in addition to providing energy needs if implemented, has the capacity to stimulate regular collection of MSW to feed a pyrolysis plant thereby reducing accumulation of the waste in communities, especially in developing countries.

**Keywords:** Pyrolysis, Combustible Gaseous Products, Municipal Solid Waste

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## **1.0 Introduction**

The steady population growth and the numerous economic activities in Ghana result in increasing MSW generation. Inadequate information on waste arising and characterisation is, however, a common occurrence in Ghana. The quantification of MSW generation and its characterisation in this research is based on estimates on data available from the Accra Metropolitan Area. The urban areas of Accra, the capital city of Ghana produce about 2000 tonnes of municipal solid waste per day (Environmental Protection Agency (EPA), 2002). According to the EPA report, by 2025, this figure is expected to increase to 4000 tonnes per day.

The management of the waste, composed mainly of paper/cardboard, plastics, glass, metals, textile, food/garden waste and others, is a serious problem in Ghana (Boadi and Kuitunen, 2002; Palczynski, 2002). The disposal of the municipal solid waste in many parts of Ghana is carried out through open dumps. Inadequate financial and human resources coupled with the absence of enabling policies, make it impossible to operate and maintain disposal sites at appreciable standards. The location of dumping sites is more often determined by access to collection vehicles rather than ecological/environmental or public health considerations. For example, waste dumped on the shores of the Korle Lagoon in the city of Accra has gradually eroded into the Korle Lagoon, leading to annual flooding over the banks of the lagoon in certain parts of the city (Boadi and Kuitunen, 2002).

While only a small fraction of the waste is recycled, greater proportion is currently disposed off via landfills (Ghana Landfills Guidelines, 2002; Palczynski, 2002). This management system does not ensure source segregation of the waste. Non biodegradable materials such as plastics find their way into the landfills. Composting and anaerobic digestion of the waste is practically unfavourable. Open-air burning of the waste in the landfills to reduce the volume and create space for further waste accumulation is the common practice nationwide. The environmental problems associated with these options of waste disposal are subjects of great concern. Most landfills are close to residential communities and have no provisions for leachate management. Figure 1 shows a waste dump close to residential facilities in a community in Ghana. In most cases the accumulated wastes in such dumps are subjected to open air burning to reduce the volume and create space for further accumulation (Buah and Ndur, 2010). This is because land availability for waste landfill is becoming exhausted. The open-air burning releases dust particulates into the air and it has the potential to emit other

toxic gases such as SO<sub>2</sub>, HCl and polyaromatic hydrocarbons (Kawanishi et al., 2013; Mark et al., 2015; Williams, 2005; Zhang et al., 2014).



**Figure 1 Open air burning of MSW at a dump site in a residential community in Ghana (Buah and Ndur, 2010)**

In several urban areas especially in developing countries the contribution to the particulate matter exposure has been demonstrated to range between 30 and 50% dependent upon weather conditions (Ravindra et al., 2001). Thermal treatment of the waste needs to consider a system such as pyrolysis which ensures less emission to the environment.

This paper presents the results of a study on recovery of combustible gases via pyrolysis of combustible fractions of MSW. Pyrolysis of MSW samples was performed under inert atmosphere of nitrogen in a static bed pyrolysis reactor, heated at a controlled rate of 10 °C min<sup>-1</sup>, to a final pyrolysis temperature of 700 °C to recover combustible gaseous product, char and oil. The yields of the pyrolysis products were quantified. The combustible gaseous product evolved during the pyrolysis was analysed off line by gas chromatography to establish the constituent gases and also to determine the calorific value of the product.

## **2.0 Materials and Methods**

### **2.1 Composition of the waste**

The material used for this test was a composite of MSW from three different waste dumps in Tarkwa in the Western Region of Ghana. Twenty informal waste carriers, who collect

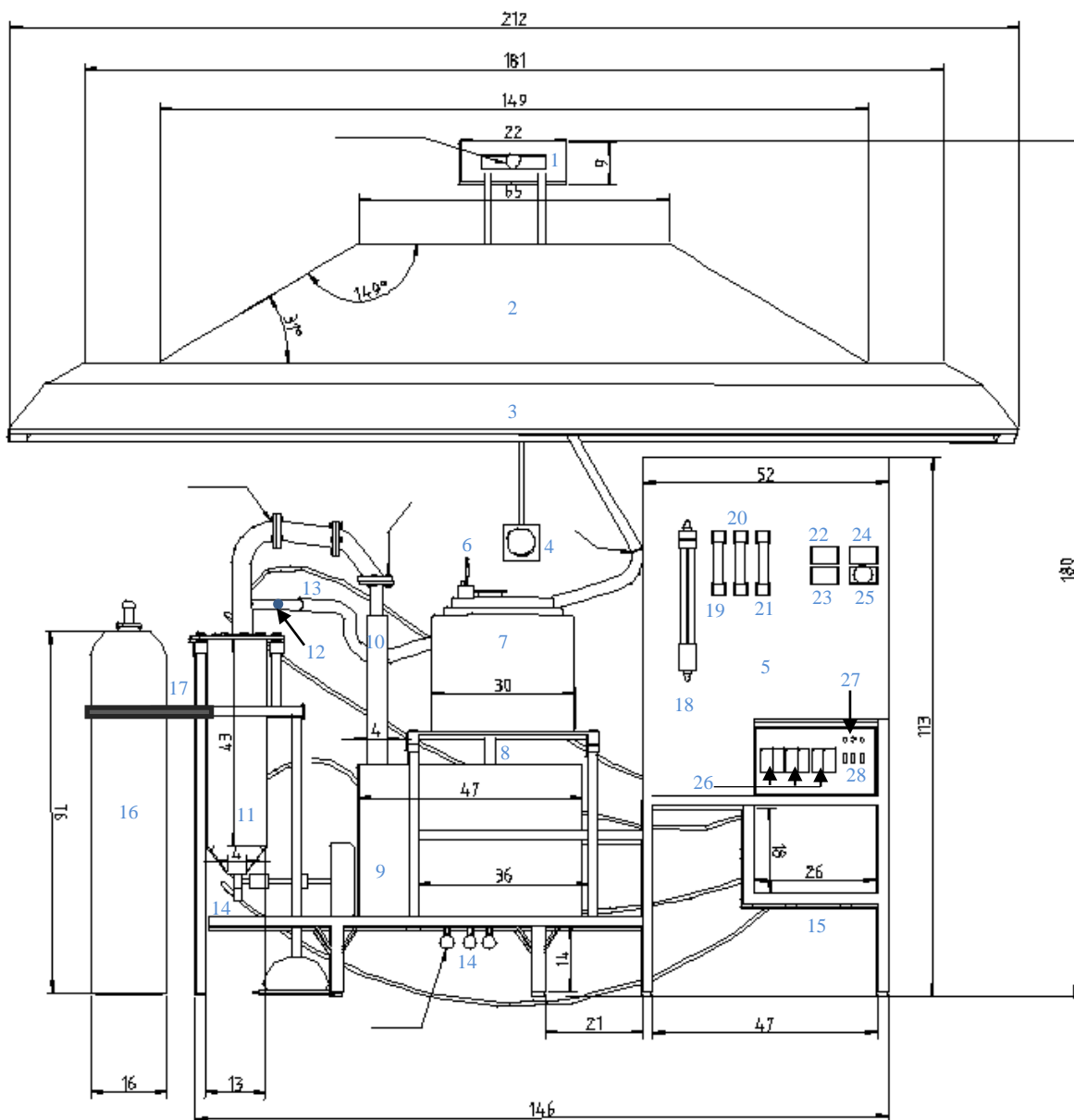
household wastes in baskets for a fee and take them to the three identified waste dumps, were contracted to composite their waste. The waste was sorted into various components, dried in the sun and the weights of the various components were determined. The waste components determination was done for seven continuous days. The easy to dry components in the waste stream: paper and cardboard, plastics and rubber, and textiles were composited and shredded as feed for pyrolysis.

## **2.2 Pyrolysis of the waste**

Pyrolysis of the MSW sample was carried out under inert atmosphere of nitrogen in a static bed pyrolysis reactor, heated at a controlled rate of  $10\text{ }^{\circ}\text{C min}^{-1}$  to a final temperature of  $700\text{ }^{\circ}\text{C}$ . The pyrolysis temperature of  $700\text{ }^{\circ}\text{C}$  was chosen because in an earlier research on characterisation of products from the pyrolysis of MSW in the form of Refuse Derived Fuel (Buah et al., 2007), it was established that evolution of  $\text{H}_2$  with lower concentrations of  $\text{CO}$ ,  $\text{CH}_4$  and other hydrocarbons gases occurred mainly between  $580$  and  $700\text{ }^{\circ}\text{C}$ . Other researchers also submit that increase in gaseous products of pyrolysis, thought to be predominantly due to secondary cracking of the pyrolysis vapours, occurs at higher pyrolysis temperatures between  $580$  and  $700\text{ }^{\circ}\text{C}$  (Ding et al., 2015; Luo et al., 2004; Onay, 2007; Song et al., 2015).

The reactor, diagrammatically shown in Figure 2, consists of a cylindrical steel reactor vessel and lid, which was surrounded by three electrical ring furnaces (7). The reactor was sealed using two concentric rings of crushed copper tubing acting as a sealing gasket between the lid and the reactor body flange, which accepts nuts to fasten the lid on top of the reactor.

Within the reactor were two perforated tubing rings at the top and bottom, which allowed the purge gas to enter the reactor. There was also a  $25\text{ mm}$  diameter steel down-tube (8) that allowed the purge gas and any vapour phase pyrolysis products to leave the reactor. The down-tube was surrounded by six housings of various heights that protected the thermocouples used to measure the sample temperature. The vapour phase produced during pyrolysis pass into a large primary condenser (9), which sits in a water tank, then through secondary and tertiary condensers (10 & 11) before entering an exhaust tube (13) into the ventilation system of the building.



**LEGEND**

- |                              |  |   |
|------------------------------|--|---|
| 1. Fume hood isolation valve | 11. Tertiary condenser                                   | 20. Rotameter for condenser cooling water flow          |
| 2. Fume hood                 | 12. Gas sampling point                                   | 21. Ditto   |
| 3. Curtain tracks            | 13. Exhaust tube   | 22. Thermocouple display for flexible probe             |
| 4. 3-Phase socket            | 14. Condenser taps                                       | 23. Thermocouple display for reactor thermocouple no. 2 |
| 5. Control and display panel | 15. Parts cabinet for rig parts                          | 24. Display for thermocouple selector dial              |
| 6. Pressure relief valve     | 16. Purge gas cylinder                                   | 25. Thermocouple selector dial                          |
| 7. Reactor and furnace       | 17. Retaining strap                                      | 26. Furnace temperature controllers                     |
| 8. Down-tube                 | 18. Rotameter for purge flow to top distributing ring    | 27. Furnace heater on indicator lights                  |
| 9. Primary condenser         | 19. Rotameter for purge flow to bottom distributing ring | 28. Furnace power on/off switches                       |
| 10. Secondary condenser      |  |   |

**Figure 2 The 3 kg Pyrolysis Reactor Assembly**

The heater controllers and furnace were powered by a three-phase electrical supply, whereas the thermocouple display panel was separately powered by a normal 13A supply. The purge gas, nitrogen flow rate through the bottom distribution ring was monitored by rotameter (18). The flow to the top distribution ring was monitored and controlled by a rotameter fitted with a needle valve (19). Water flow to the condenser was monitored and controlled by two further rotameters (20 & 21).

Temperature indicators permanently displayed the temperature measured by a flexible probe in the reactor (22) and half-way up the sample bed (23). Three temperature controllers (26) regulated the reactor furnaces. The power state of the furnace was indicated by three lights above the switches, shown as (27).

A mesh grate was used to separate the feedstock off the reactor floor, which was often cooler than the rest of the reactor. The weighed sample is loaded into the reactor ensuring that the stock level was below the level of the down-tube. The reactor was then covered and sealed making sure the two sealing rings were in place and heated to a final pyrolysis temperature of 700 °C at a heating rate of 10 °C min<sup>-1</sup>. A pressure relief valve was provided on the reactor lid. At the end of the run period the reactor was switched off and allowed to cool overnight. The product char and oil were then collected taking the necessary health and safety precautions.

### **2.3 Analysis of the pyrolysis products**

The products obtained from the pyrolysis of the MSW; carbonised MSW (char), gaseous and liquid products were analysed as follows:

Carbonised MSW sample: Representative sample of the char obtained from pyrolysis of the MSW was crushed to <math>-2.00\text{ mm}</math>, dried at 110 °C for 24 h and analysed for surface area by the nitrogen adsorption technique using a Micromeritics Tristar 3000 instrument. A standard bomb calorimeter was used to determine the calorific value and sulphur content of the char sample. The proximate analysis on the char sample was carried out using a Shimadzu TGA-50H Analyser and a FlashEA 1112 analyser was used to carry out elemental analysis.

Liquid products: The liquid fraction comprised a viscous oil/wax phase and an aqueous phase. The two phases were separated using a high speed centrifuge. The calorific value and combustible sulphur contents of the viscous oil/wax phase were determined using a standard procedure by bomb calorimetry followed by volumetric analysis. Fourier transform infrared (FTIR) was also used to determine the functional groups in the oil fraction.

Pyrolysis gases: The gases obtained from the pyrolysis were sampled at various time intervals by means of gas syringes and analysed off line by packed-column gas chromatography for CO, CO<sub>2</sub>, H<sub>2</sub>, CH<sub>4</sub> and other hydrocarbon gases. The gases were immediately analysed via two packed column gas chromatographs, one for permanent gas analysis and one for hydrocarbon gas analysis. A Varian CP-3380 gas chromatograph with two packed columns and with two thermal conductivity detectors (GC/TCD) and argon carrier gas was used for the analysis of the permanent gases. Hydrogen, oxygen, carbon monoxide and methane were analysed on a 2 m length by 2 mm diameter column, packed with 60–80 mesh molecular sieve. Nitrogen, the purge gas used in the fixed bed reactor, was also determined, and the volumetric flow rates of the evolved gases were calculated by comparison with the N<sub>2</sub> flow rate. Carbon dioxide was analysed on a 2 m length by 2 mm diameter column with Haysep 80 – 100 mesh packing material. The gas chromatograph oven was held isothermally at 30°C for the analysis; the injector oven was at 120°C. The detector oven operated at 120°C with filament temperature of 160°C.

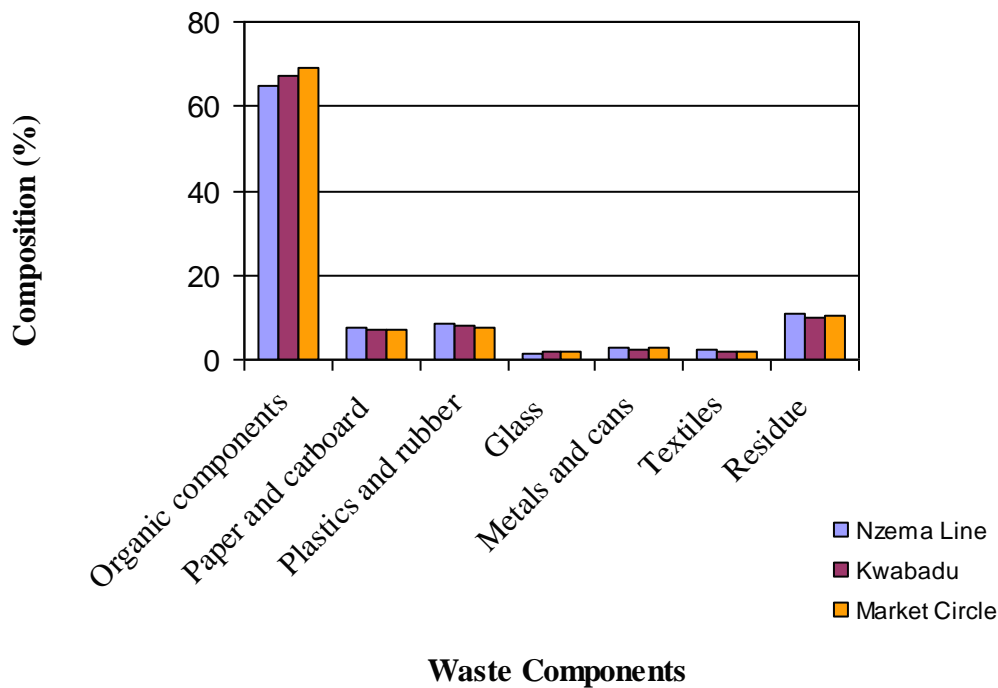
Hydrocarbons from C<sub>1</sub> to C<sub>4</sub> were analysed using a second Varian CP-3380 gas chromatograph with a Flame Ionisation Detector (GC/FID). The column used was 2 m long with 2 mm diameter packed with 80 – 100 mesh Hysesp. Nitrogen was used as the carrier gas. The temperature was programmed to start at 60 °C for 3 min, ramped at 10 °C min<sup>-1</sup> to 100 °C, held for 3 min, finally ramped to 120 °C at 20 °C min<sup>-1</sup>, and held for 9 min at 120 °C. The injector was held at 150 °C while the detector temperature was 200 °C.

### **3.0 Results and Discussion**

#### **3.1 Composition of the waste**

It was found out that the types of materials in the waste streams going to the three different waste dumps were about the same except that they differed in their proportions. The average composition of the various components in the waste stream is shown in Figure 3.





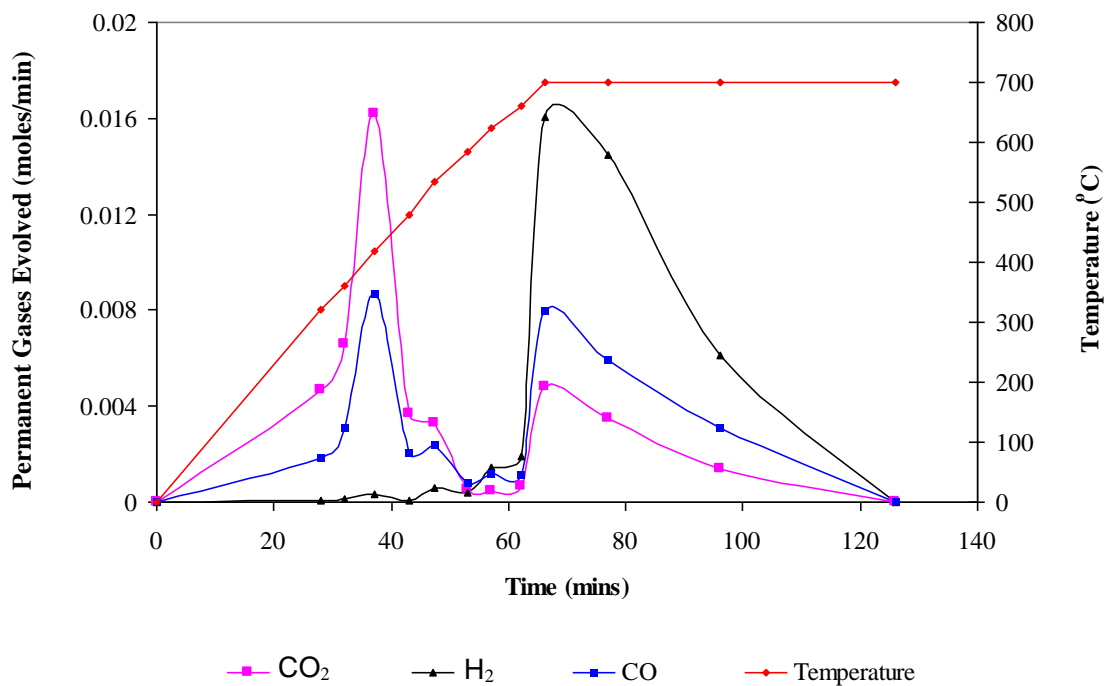
**Figure 3 Composition of MSW in Selected Waste Dumps in the Tarkwa Area**

The main components in the waste were organic materials, paper, cardboards, plastics, rubber, glass, metals, textiles and residue. The variations in the composition of the waste in the three dumps could be attributed to socio-economic factors such as levels and patterns of consumption, reuse and recycling practices prevailing in the studied zones. The influence of socio-economic conditions on waste composition is supported by the works of Taboada-González et al. (2010) and Afroz et al. (2011).

The organic components in the waste stream constitute about 67 wt%. Palczynski (2002) also reported on a research work on waste management in Africa that waste generated in developing countries has food remains as the largest fraction, ranging between 35 – 80 wt%. Some of these organic components in the waste were very difficult to dry because of their moisture content and may not easily undergo direct thermal decomposition. For this reason only the easy to dry combustible fractions were composited for pyrolysis. The composition of the reconstituted MSW was 41.81 wt% paper and cardboards, 45.20 wt% plastics and rubber and 12.99 wt% textiles. It is envisaged that the organic fractions of the waste may find suitable processing applications in compost production.

### 3.2 Gaseous Components of the MSW Pyrolysis

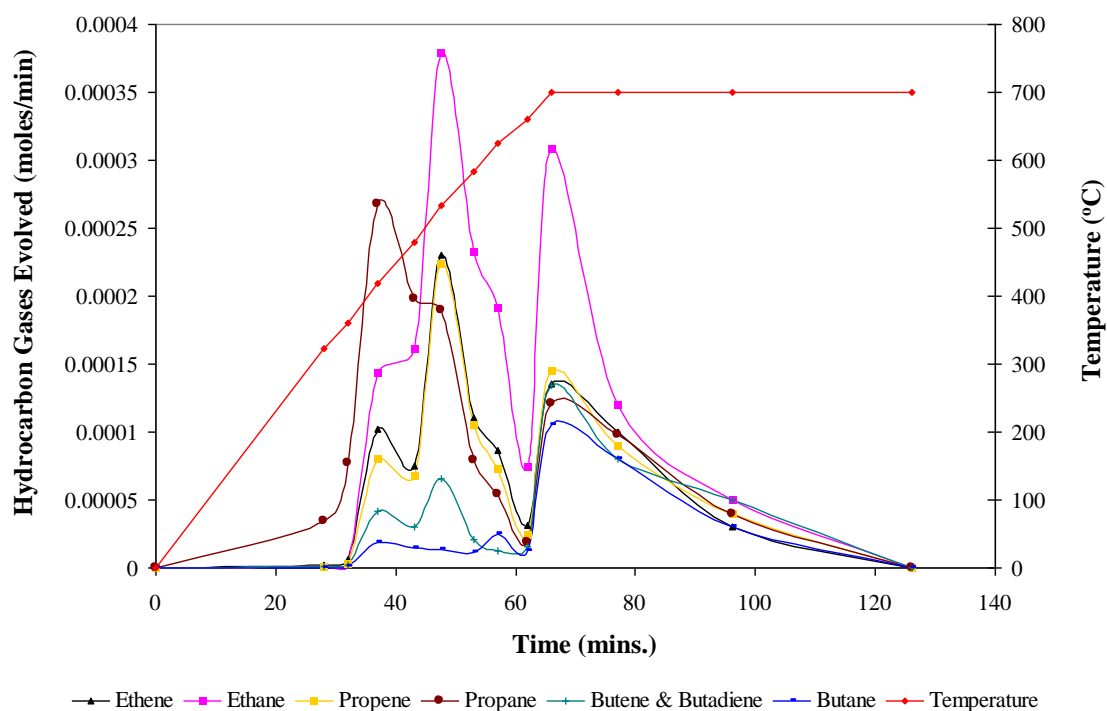
Analysis of the gaseous product from the MSW sample pyrolysed to the final pyrolysis temperature of 700 °C showed the main gases to be CO<sub>2</sub>, CO, H<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub> and C<sub>3</sub>H<sub>8</sub> with lower concentrations of other hydrocarbon gases. The gases are produced from the thermal degradation reactions of the waste constituents as they breakdown and also through secondary cracking reactions of the primary products. The evolution of permanent and hydrocarbon gases during pyrolysis to a final temperature of 700 °C occurred mainly within two temperature ranges as shown in Figures 4 and 5 respectively.



**Figure 4 Evolution of Permanent Gases During Pyrolysis of the RDF to a Final Temperature of 700 °C**

Evolution of CO and CO<sub>2</sub> occurred mainly at lower temperatures, between 200 and 480 °C, and H<sub>2</sub> with lower concentrations of CO and CO<sub>2</sub>, CH<sub>4</sub> and other hydrocarbons at higher temperatures between 580 and 700 °C. The gross calorific value calculated from the gas analysis data of the gas, which was sampled when the pyrolysis of the MSW reached a temperature of 700 °C was 18.0 MJ m<sup>-3</sup>. This represents a significant calorific value when compared to that of natural gas of approximately 37 MJ m<sup>-3</sup>. The relatively high calorific value of the pyrolysis gaseous product suggests their potential use to provide process fuel.

The high concentration of carbon dioxide and carbon monoxide in the product gases is derived from the oxygenated structures in the original material, such as cellulose, hemicellulose and lignin. The compositions of the major products from pyrolysis of various carbonaceous materials have been shown to depend on temperature (Ding et al., 2015; Song et al., 2015; Uzun et al., 2007).



**Figure 5 Evolution of Hydrocarbon Gases During Pyrolysis of the RDF to a Final Temperature of 700 °C**

### 3.3 Yield of the pyrolysis products

The mass balance of products obtained from the pyrolysis of the MSW was determined by weighing the char and oil fractions while the yield of the gaseous component was calculated by difference. The yield of the combustible gaseous product was 23.01 wt% and that of the char and oil fractions were 32.00 wt% and 44.99 wt% respectively. The char had a specific surface area of 82.00 m<sup>2</sup> g<sup>-1</sup>, calorific value of 11.40 MJ kg<sup>-1</sup> and contained 50.00 wt% C, 0.77 wt% H, 0.92 wt% N, 0.20 wt% S, 6.11 wt% O and ash. The proximate analysis of the char showed that it contained 0.30 wt% moisture, 16.60 wt% volatile matter, 40.90 wt% fixed carbon and 42.00 wt% ash. The oil product, after separation of its water content, was analysed to have a calorific value of 35.50 MJ kg<sup>-1</sup>. FTIR spectrometry of the oil fraction

indicated the presence of carboxylic acids and their derivatives, alkanes, alkenes, mono and polycyclic and substituted aromatic groups.

#### **4. Conclusions**

Recovery of combustible gases has been achieved via pyrolysis of combustible fractions of Municipal Solid Waste. The combustible gaseous product, analysed off line by gas chromatography contained mainly CO<sub>2</sub>, CO, H<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub> and C<sub>3</sub>H<sub>8</sub> and has relatively high calorific value of 18.0 MJ m<sup>-3</sup> making the gas suitable for use as a fuel. The significance of this research is that the pyrolysis recovered combustible gas can now be stored conveniently and easily transported for various applications. Again, recovery of the gaseous product from the waste has the potential to stimulate regular collection of MSW to feed a pyrolysis plant thereby reducing accumulation of the waste in communities, especially in developing countries.

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