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Performance of Small-Scale Waste Incinerators and Emission Levels – Case Study of Egerton University and its Environs, Kenya

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***Abstract*—Waste incineration process involves chemical reaction of organic constituents with oxygen to produce flue gases, heat energy and other residues. The flue gases may contain heavy metals which have become a threat to human health and other living organisms. The study investigated the effects of varying: moisture content; loading rate; operating temperature and types of waste on incineration performance – composition of emitted flue gases (carbon monoxide, carbon dioxide and hydrocarbon) including oxygen depletion levels. Samples of waste were weighed and placed centrally into the combustion chamber and ignited. The gas pick-up probe was connected at the chimney to pick the flue gases for analysis. Incinerating wastes with moisture content of 65, 45 and 25% yielded mean carbon dioxide emissions of 10, 7 and 5%, carbon monoxide at 7, 5 and 4 ppm and hydrocarbon at 916, 730 and 618 ppm, respectively. Waste incineration at loading rates of 45, 30 and 15 kg yielded carbon dioxide of 10, 8 and 6%, carbon monoxide of 8, 6 and 4 ppm and hydrocarbon of 945, 720 and 577 ppm, respectively. Incineration at temperatures of 850, 650 and 450ºC yielded carbon dioxide of 7, 9 and 12%, carbon monoxide at 6, 8 and 10 ppm and hydrocarbon yielded 644, 855 and 1293 ppm, respectively. Incineration of domestic, agricultural, institutional and commercial wastes yielded carbon dioxide emissions of 6, 8, 12 and 10% while carbon monoxide at 6, 8, 13 and 11 ppm and hydrocarbon at 671, 869, 1244 and 1095 ppm, respectively. The increase of carbon monoxide and hydrocarbon contents in the flue gas was a strong indication of inappropriate burning conditions in the furnace. Dark and dense smoke indicated incomplete waste combustion due to incinerator overloading, high moisture content, low operating temperatures and poor air/waste ratios. The low moisture content, light incinerator loading rates, high operating temperatures and well-mixed types of waste yielded low smoke density, small particle size distribution and high quality bottom ash residues. A properly controlled combustion process and furnace design would achieve high combustion efficiency and operating temperatures, better waste loading rates, a well-mixed waste, improved fuel system and air circulation. It would also lead to low moisture content and low emission of flue gases.**

Keywords*— *Performance; small-scale incinerators; moisture content; Incineration; loading rates; operating temperatures; waste types; emissions; smoke density; bottom ash.

1. INTRODUCTION

The waste incineration process reduces the organic and combustible waste to non-combustible matters like ash and results in weight reduction that can safely be disposed of on land, or in underground pits [1]. It involves sequential steps such as drying, volatilization, combustion of fixed carbon and char burnout, combustion of vapours, gases and particulate residues. The combustion process extremely depend upon the incinerator design, high-temperature air mixture to produce enough combustible gases, long-resident time to allow complete oxidation and adequate turbulence in the combustion gas mixture [2]. The flue gas pressure in the stack/chimney must carefully be controlled to ensure that all the gases are removed from the combustion zone at the correct rate.

The emission standards for incinerations require the use of Air Pollution Control Devices (APCD), monitoring, inspection and permitting programs. ENVILEAD, (2005) [3] noted that the incinerator at Kenyatta National Hospital (KNH) do not have APCD. The KNH incinerator emits noxious fumes to the neighborhood causing considerable distress to the residents. The product of incomplete combustion range from low molecular weight hydrocarbon such as methane to high molecular weight compounds such as dioxins and furans which cause serious health effects [4]. Tangri (2003) [5] noted that 90-95% of human exposure to dioxins is from food, particularly meat and dairy products due to accumulation in fats and oils. Some of the probable health effects of dioxins and furans include the development of cancer, immune system suppression, reproductive and developmental complications, endocrine disruption [6]. The accumulation of dioxins and furans in the environment due to waste incineration activities can reach levels that render resources unfit for human consumption - even low doses of dioxins are very toxic.

The aim of this study was to determine the effects of varying moisture content, loading rate, operating temperature and waste category on performances of selected small-scale domestic incinerators - the composition of flue gases emission including Carbon Monoxide (CO), Carbon Dioxide (CO_2), Hydrocarbon (HC) and Oxygen (O_2) depletion levels. The main problems associated with waste incineration processes are the large volume of gaseous emissions which may pose

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environmental health risks and hazardous solid wastes - fly ash, bottom ash or APCD residues that remain after incineration [7, 8]. The bottom ash accounts for 90% of the residue and consists mostly of alumina, silica, oxides of iron, salts of chlorine-contents and wide variety of heavy metals. The incineration bottom ash is highly toxic and handling of it raises serious concerns to workers who are often exposed to it, sometimes with little or no protective gear [9, 10]. The bottom ash is usually dumped in insecure landfills such as unlined pits which run the risk of contaminating groundwater. Sometimes the dioxin-rich bottom ash finds its way into towns' dumpsites [11]. Fly ash consists of smaller and lighter particles entrained in flue gases that were collected in the APCD and mixed with used scrubber sorbent. The CO arises in combustion chambers where there is deficiency of oxygen (O_2) for full oxidation. Volatile organic compounds are products of incomplete combustion and may cover a wide range of compounds since they include carbon chains or rings that have high vapour pressure.

The waste incineration also produces the greenhouse gases (GHG) consisting of CO_2, methane (CH_4), nitrogen dioxide (N_2O), chlorofluorocarbons (CFC) and ozone (O_3) in the atmosphere [12]. The GHG causes sporadic changes in weather patterns and could eventually make parts of the planet uninhabitable [13]. The Kyoto Protocol requires the signatory states to be committed in GHG emissions reduction. The incinerator design, moisture content (MC), waste heating value, waste types, loading rate and percentage of inert material are important parameters in emissions consideration. Since MC is in effect water and a non-burnable component in the waste, it has to be minimized for it to be vaporized in the combustion drying phase. Low MC reduces the energy required to dry the waste, energy available to volatize vapors and provide necessary gas temperatures to complete the destruction of the unburned gases, vapours, and particulate matters.

2. MATERIALS AND METHODS

2.1 Study Area and Materials Preparations

This research was conducted at Egerton University in the Agricultural Soils and Animal Science Nutritional Laboratories between May and September, 2015. The average ambient temperatures ranged between 19-24°C. Solid waste samples were collected from the University dumping site (student cafeterias, departments of Crops, Horticulture and Soil, Animal Health, Human Anatomy, Medical) and neighbouring residential estates (Njokerio, Ngondu, and Green Valley). Waste samples were prepared by drying for three days, chopping into small pieces and packing separately as per their types. The samples were reduced further to less than 1mm size to form a homogenous material in order to increase surface area which would allow easier heat penetration. They were then packed, labelled and stored in sealable polythene bags to prevent any changes in their physical and chemical properties. The waste samples were fed into the furnace without pretreatment and selection of specific ingredients. The samples were weighed and recorded before the incineration processes started.

2.1.1 Experimental set-up

The equipment required in this study entailed a well-insulated muffle furnace Lindberg/Blue MBF51700 used for waste incinerations, different small-scale incinerators, flue gases analyzer MS 805, digital electrical meter and the electrical power supply. Others were an electronic digital weighing balance, furnace crucibles, drier, timer and cutting/shearing machine plus materials such as nose mask, gloves and clear goggles. Figure 2.1 shows the experimental machine set-up.

2.1.2 Muffle furnace incineration

The experiments on varying moisture content, various types of waste and varying operating temperatures were done using the muffle furnace. An empty crucible was weighed and a 50 g of the waste sample put on it. The weighed crucible and the sample were placed centrally inside the muffle furnace chamber and the door closed. The furnace was connected to the power supply and was well grounded. All electrical connections were checked for proper insulation and secured firmly. The exhaust vent was fully opened to remove unwanted vapours and gases from the furnace chamber. The arrow keys were used to adjust the operating temperature and set/enter key pressed on to register the changes. The power was switched on by pressing 'Run' button and the control panel started to blink. For safety reason, no flammable and explosive materials were incinerated in the furnace. Also, high concentration of sulphates, chlorides, fluorides, alkaline, plastics, polythene papers, rubbers and other combustible products were avoided due to their corrosive effects on the ceramic fiber and explosiveness. All the experiments using muffle furnace took a maximum time of 150 minutes and a cool down of ten hours.

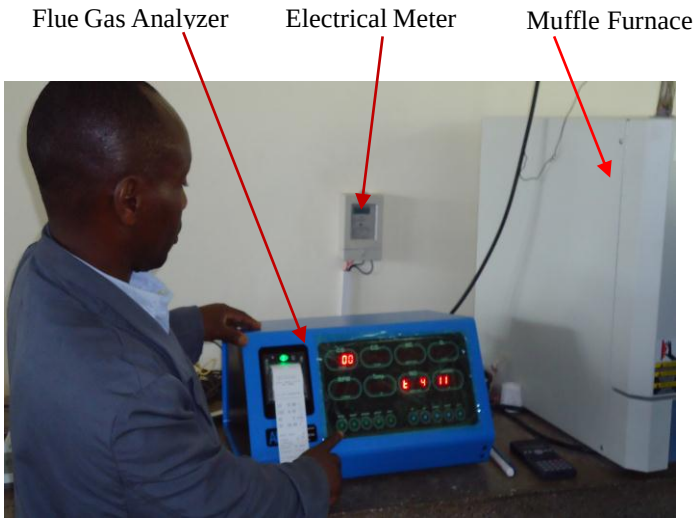

Figure 2.1: Researcher setting up the experimental equipment.

2.1.2 Flue gas analysis

The MS 805 flue gas analyzer was configured to measure carbon dioxide emissions and oxygen depletion levels in percentage (%) and carbon monoxide and hydrocarbon in parts per million (ppm). The gas pick-up probe with its hose was connected to the chimney/stack of the muffle furnace. The gases sampled by the probe connected to the induction coupler passed through the vertically positioned gross plastic filter

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before reaching the first cup of the steam trap located at the bottom of analyser. The filter were made of several plastic granules which increased the contact surface area and held much of the humidity condensation. The obtained condensation was then sucked through an opening on the lower part of the separator from the "water" side of the pump and ejected. The filtered gases was sampled from the coupler positioned at the top of the first cup and then conveyed to the filter housed within the second cup at the top position. From the top of the cup the cleaned gas was then conveyed to the solenoid valve which either intercepted the gas and injected clean air during the resetting phase or let it flow through the other steps. When the gas reached a duct inside the trap base it branched into three different pipes: one fitting into the vacuum sensor which detected any possible anomaly in the gas flow or leak in the pneumatic circuit; the other connecting to the gas in the port through which the sampled gas was charged during calibration and the last pipe connecting to the pump gas side through a safety paper filter. Eventually, the gas was charged to the CO, CO_2, HC and O_2 sensors for measurement via the measuring bench before purging it outside. Then a printer was used to produce hardcopies of the final reports of the tests carried out.

2.1.3 Combustion processes

The combustion processes were complex which involved simultaneous coupled heat and mass transfer, chemical reaction and fluid flows. Increasing the amount of air above the stoichiometric point would lower the combustion temperature because energy would be used to heat the combustion air from ambient temperature to the combustion chamber temperature [14, 8]. The wastes combustion equation was represented using Equation 2.1.

$$C_{x1}H_{x2}O_{x3}N_{x4}S_{x5}Cl_{x6}Si_{x7}K_{x8}Ca_{x9}Mg_{x10}Na_{x11}P_{x12}Fe_{x13}Ti_{x15} + a_1H_2O + a_2(1+e)\,(O_2 + 3.76N_2) \rightarrow a_3CO_2 + a_4H_2O + a_5O_2 + a_6N_2 + a_7CO + a_8CH_4 + a_9NO + a_{10}NO_2 + a_{11}SO_2 + a_{12}HCl + a_{13}HC + a_{14}KCl + a_{15}K_2SO_4 + a_{16}C + \ldots + \text{Heat Energy} \quad (2.1)$$

Where; a_1 = the moisture in waste;

a_2 = Amount of air (mixture of O_2 and N_2) used in the combustion;

1+e = Excess air in relation to the stoichiometric amount,

(usually ranges from 1.2 to 2.5 of air/waste ratio);

a_3 to a_{16} = The stoichiometric coefficients of the different species that can be found as reaction products, among many others that can be released in the emissions.

The burning of compounds containing oxygen require less air since the compound already contains some oxygen that would be available during the combustion process. A typical waste stream component like cellulose, a major constituent in waste paper products, would be combusted according to equation 2.2 [14].

$$C_6H_{10}O_5 + O_2 + (19.97N_2) \rightarrow 6CO_2 + CO + O_2 + 5H_2 + (19.97N_2) + 23{,}342\ \text{KJ/Kg} \quad (2.2)$$

2.2 Solid waste incineration processes

This section involved the emission-level processes during waste incineration at varying: moisture content, incinerator loading rate, operating temperatures and waste categories. The photographs for waste collection points, waste bins, disposal dump sites and small scale incinerators were taken. The muffle furnace could only operate effectively at a maximum temperature of 850°C. During pilot experiments, the selection of the range and values of the process parameters was guided by machine specifications. The periods taken for each complete cycle of waste incinerations were 60, 90, 120 and 150 minutes. The maximum period of 150 minutes was adopted for all muffle furnace incineration processes since the combustion was considered complete upon reaching an oxygen concentration of greater than 20.6% in the flue gas [8] whereas maximum time of 90 minutes was adopted for all small-scale incinerators processes. The smoke density was also observed and noted. The bottom ash after cooling down to room temperature was weighed and packed in a labelled polythene bag for further analysis.

2.2.1 Effects of moisture content on emission levels

The solid waste at varying moisture content (MC) ratios of 25, 45 and 65% by weight were incinerated separately using the muffle furnace. The ratios were chosen taking into account the tabulate commercial waste MC mean value of 46.51% and were obtained through rewetting and drying of the waste in an oven. Samples of 100g were taken in triplicate, dried to a constant weight in an oven at 105°C for twelve hours, cooled in a desiccator and the difference in weight recorded. Some water was added to the other samples in the correct proportions in order to obtain the MC of 65%. Samples of 50g at MC ratio of 45% were separately loaded into the crucible, placed into the furnace and incinerated at 850°C. The flue gases flowing at the chimney was passed through the flue gas analyzer and CO, CO_2 and HC emission and O_2 depletion levels recorded for analysis. The same procedure was repeated for the other MC ratios.

2.2.2 Variations of incinerator loading rate and its emissions

This experiment was conducted using the small-scale incinerator at Janda Plaza near Egerton University main gate opposite the Njoro Canning Factory. The samples used were from commercial waste which had a mean MC value of 46.5%. The incinerator loading rate ratios used were 45, 30 and 15 kg. These ratios were arrived at since the used incinerator had a normal waste capacity of 29 kg. The waste samples of low, medium and high heating values were thoroughly mixed to emulate the normal incinerator loading before being used. Since the incinerators were loaded manually then they were charged when cold. The incinerator door was closed to prevent air infiltration into the primary chamber. The CO, CO_2 and HC emissions and O_2 depletion levels for each experiment were recorded. The smoke density behaviour was noted and photographs taken. The bottom ash was packed separately in polythene papers for analysis after cooling down for ten hours. The maximum time taken by one experiment was 90 minutes. The procedure was repeated for each incinerator loading ratios.

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2.2.3 Emissions due to different waste categories incineration

The solid waste categories incinerated in a muffle furnace were domestic, agricultural, institutional/industrial and commercial which were sorted out manually. A waste sample weighing 50 g in a crucible was placed centrally into combustion chamber of the muffle furnace, temperature set at 850ºC, flue gas analyser installed and the equipment switched on. The emission levels were recorded. The smoke density was noted and the bottom ash packed for more analysis after cool-down. The same procedure was repeated for the other waste categories.

2.2.4 Emissions at varying operating temperatures

This experiment was conducted using a muffle furnace with adjustable operating temperature settings. The waste samples were incinerated at operating temperatures of 850, 650 and 450ºC, respectively. The temperature of 850ºC was chosen as the highest since the furnace could not operate above 900ºC. A waste sample of 50 g in a crucible was placed into the furnace chamber and the door locked. The gas pick-up probe with its hose was securely connected at the chimney and the furnace and flue gas analyser switched on. As the flue gases passed through the analyser the emission levels were recorded. The smoke density was also noted and photographs taken. Bottom ash was also packed into polythene bags after cooling down. The same procedure was repeated for the other operating temperatures.

2.3.1 Observation of smoke density

A simple monitoring technique of flue gas opacity was through observation of the stack emissions. The smoke density was observed and noted when incinerating waste at varying MC ratios of 65, 45 and 25%. The comparisons were done to determine the ratio which yielded dark and dense smoke with excessive particulate matter against one which yielded light and clear smoke. The same procedure was repeated for incineration of various waste categories, varying incinerator loading rates and different operating temperatures.

2.3.2 Bottom ash residue

The incinerator start-up began with removal of the bottom ash from the previous operation cycle. The muffle furnace and incinerators were allowed to cool-down for ten hours for safe and sufficient removal of bottom ash. A flat blunt shovel was used for clean-up, rather than sharp objects to avoid damaging the refractory material. A manually operated stirrer was used to drop the generated ash, through the metal grates into ash trays at the base of the chamber. The final step in the cycle was the examination of the bottom ash quality. The bottom ash was examined for the unburnt materials like pieces of wood, paper remains and the colour which indicated poor incinerator performance. The weight of bottom ash (W_{as}) collected at the end of each incineration processes was compared with the total waste loaded (W_t) and packed into marked polythene bags. The weight loss due to incineration (W_r) was determined using equation 2.3 while the percent weight reduction (P_{wr}) was calculated using equation 2.4.

$$W_r = W_t - W_{as} \quad (2.3)$$

$$P_{wr} = \frac{W_t - W_{as}}{W_t} \times 100 \quad (2.4)$$

3. RESULTS AND DISCUSSIONS

3.1 General Findings

The residents of Egerton University and its surroundings have ideas of clean environment which has led to many of them building small-scale waste incinerators. However, assessment of those incinerators revealed notable deficiencies in the design, construction, siting, operation and management of the units. Those deficiencies have resulted in poor performance including low temperatures, incomplete waste destruction, inappropriate ash disposal, high smoke emissions and fugitive (particles which escape into the environment as fly ash from combustion chamber) emissions. It was noted that, user acceptance of small-scale incinerators was generally high and their use was preferable to the disposal of waste in unsecured pits or landfills, or uncontrolled open burning in drums or pits which agreed with findings by [9]. The waste incineration experiments were repeated three times and graphs of means, standard deviations and the Least Significant Different (LSD) discussed in the following sections.

3.2 Waste Incineration Emission Levels

This section included waste incineration at various moisture contents, incinerator loading rates, waste categories and operating temperatures. The mixing of waste was influenced by the shape and the size of combustion chamber and how air was injected. Low temperatures, low heating values of the waste and reduced turbulence resulted in increased holding time to complete the combustion processes. All the above parameters affected the incinerator's performance and were discussed in terms of their emissions including CO, CO_2 and HC and O_2 depletions, smoke density and bottom ash residuals in the following sections.

3.2.1 Emission levels at varying moisture content

Table 3.1 in the appendix shows different emission levels obtained when incinerating waste at varying moisture content. The unpleasant odours and liquids associated with wastes were due to the putrescible organic components in food and plant wet stream, which contaminate and complicates the incineration processes. If wet putrescible materials were separated it would increase the waste heating value being burned and reduce the emissions. It would also require the use of auxiliary fuel to raise the furnace temperature and to ensure normal combustion [15].

a) Carbon dioxide (CO_2) emissions

The carbon dioxide emissions emitted through incineration was affected by the MC of waste components. Figure 3.1 shows carbon dioxide emissions from waste incineration at varying MC. Incinerating waste at MC ratios of 65, 45 and 25% yielded mean CO_2 emissions of 10.1, 6.5 and 5.1% by weight, respectively. The CO_2 emissions from MC ratios of 65, 45 and 25% increased with time towards maximum values of 24.4, 15.1 and 13.3%, respectively at the 50th minute after

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which it decrease gradually. The results for MC ratio of 65% agreed with findings by [16] who noted that the national and global estimates of CO_2 emissions from fossil fuel combustion varied from 9.2 to 11.5% in 2007. The results for 25% MC ratio agreed with the report by [17] that CO_2 emission concentration from flue gas ranged between 5 and 5.9% for municipal sewage sludge mono-combustion furnace. At the peaks, much of what was contained in the waste in terms of volatile matters and fixed carbon had been broken up and released into heat energy. The waste charge containing high MC with low volatile matters required more time to burn an equivalent volume of waste which resulted to use of auxiliary fuel [18].

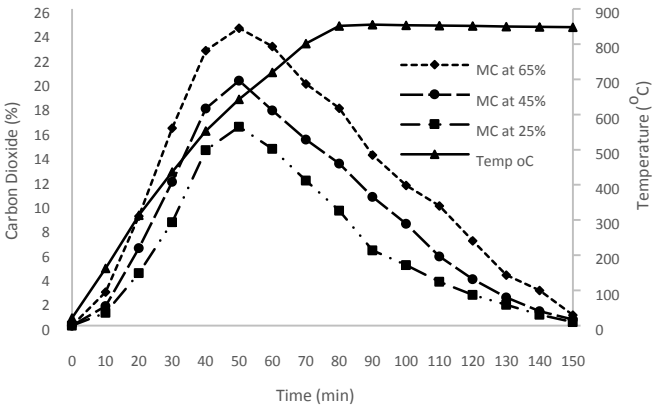

Figure 3.1: Carbon dioxide at various moisture contents.

b) Carbon monoxide (CO) emissions

The carbon monoxide is a toxic, flammable, colourless and odourless gas which is slightly lighter than air and slightly soluble in water. The CO contains significant amount of energy that could completely be burned, hence efforts must be made to minimize its formation. Figure 3.2 shows carbon monoxide emissions from waste incineration at varying moisture content. The MC ratios of 65, 45 and 25% yielded mean CO emissions of 7.2, 5.6 and 4.6 ppm which increased with time towards maxima of 12.7, 15.4 and 9.8 ppm, respectively at the 60th minute before starting to decrease. At the peaks of emissions, O_2 levels was lowest since it had been consumed during the combustion process leading to formation of carbon monoxide. The CO parameter baseline showed sharp peak emissions due to sudden variations in the combustion conditions. The insufficient air in the incinerator resulted to high CO concentration in the region towards the middle of combustion process. Botter *et al*., (2002) [19] reported that CO could be bound by blood haemoglobin stronger than oxygen to form carboxyhaemoglobin (COHb) which inhibit the supply of oxygen to body tissues. Exposure to CO could affect the cardiovascular system, central nervous system, foetus and other organs that are oxygen deficient. Heart and lung disease patients are the most sensitive group to CO exposure [20].

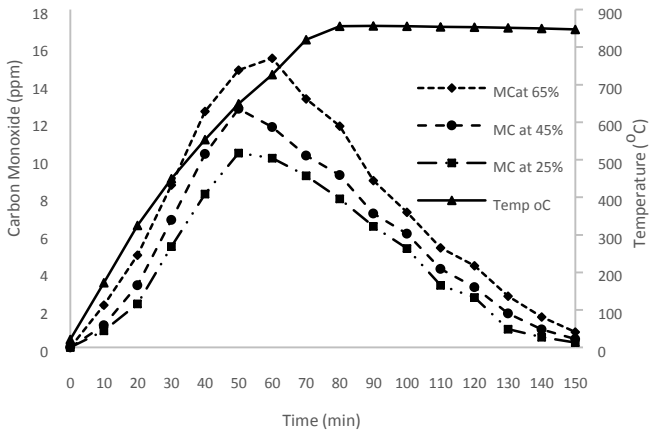

Figure 3.2: Carbon monoxide at varying moisture content.

c) Hydrocarbon (HC) emission

The formation and release of hydrocarbon is strongly dependent on the combustion conditions in the system including the combustion temperature, the residence time, turbulence, air to waste ratio, waste loading rate, carbon to hydrogen ratio in the waste and the presentation of the loading material [21]. Figure 3.3 shows the hydrocarbon emission when incinerating solid waste at varying MC. The waste incineration at MC ratios of 65, 45 and 25% yielded mean HC emissions of 916, 730 and 618 ppm, respectively. The HC emissions from MC of 65, 45 and 25% increases with time towards maximum of 1779, 1482 and 1324 ppm, respectively at the 60th minute, after which it started decreasing. High MC would reduce combustion efficiency resulting to high levels of HC emission. The incineration of polythene papers, plastics and rubbers waste released large amount of HC emissions [7]. The plastics comprising polymers, polythene papers and rubber discharged large amount of particulate matter and smoke density, due to extended period of incomplete combustion [22].

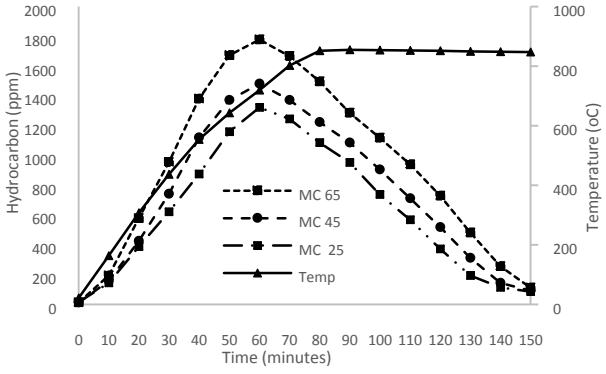

Figure 3.3: Hydrocarbon emission at varying moisture content.

d) Oxygen (O_2) depletion levels

The presence of oxygen gas in the flue gas indicated that extra combustion air was supplied than was needed for complete combustion to occur. The portion of O_2 that had not been consumed by the combustion process remains as part of the flue gas and was a measure of the combustion efficiency.

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Figure 3.4 shows the oxygen depletion levels when incinerating waste at varying MC. Waste incineration at varying MC of 65, 45 and 25% yielded mean O_2 depletion levels of 11.8, 13.1 and 14.1%, respectively. The combustion took place when waste reacted with the O_2 to produce heat energy. Complete combustion occurs when all of the energy in the waste are extracted and none of the carbon and hydrogen compounds are left. Combustion was considered complete upon reaching an oxygen concentration of greater than 20.6% in the flue gas [7]. The results disagreed with the findings by [17] who reported that O_2 depletions concentration of the flue gases amounted to 11.7% at 950ºC from municipal sewage sludge and coal co-combustion furnace. During the combustion process the oxygen would combine with hydrocarbons to form carbon dioxide and water, leaving no oxygen or HC in the flue gases. Oxygen was used in determination of combustion parameters and acts as reference value. Although not a harmful emission, the flue gases should contains very small percentage of oxygen (unused air during the combustion process).

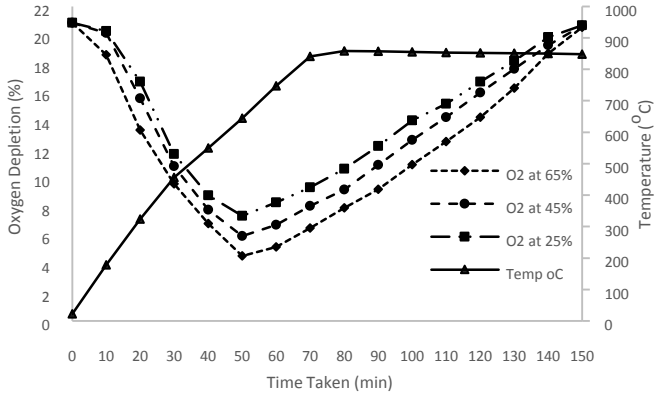

Figure 3.4: Oxygen depletions at varying moisture content.

3.2.2 Flue gases emission at varying incinerator loading rate

The incinerator waste loading rate is a measure of incineration performance. The mixture of low, medium and high calorific values in each loading was made to march with the designed heat release rate of the incinerator. The light type of waste was placed at the bottom and heavier on top and sometime mixed to balance the value of each loading. The overloading of incinerator resulted into increased emissions and incomplete waste combustion noted by bottom ash containing unburnt waste particles and dark and dense smoke at the chimney exit [23]. Table 3.2 in the appendix shows the emission levels of CO_2, CO and HC emissions and O_2 depletion levels when incinerating waste at varying incinerator loading. Figure 3.5 shows non-performing small-scale incinerator due to poor design, which resulted to open-waste burning outside the unit.

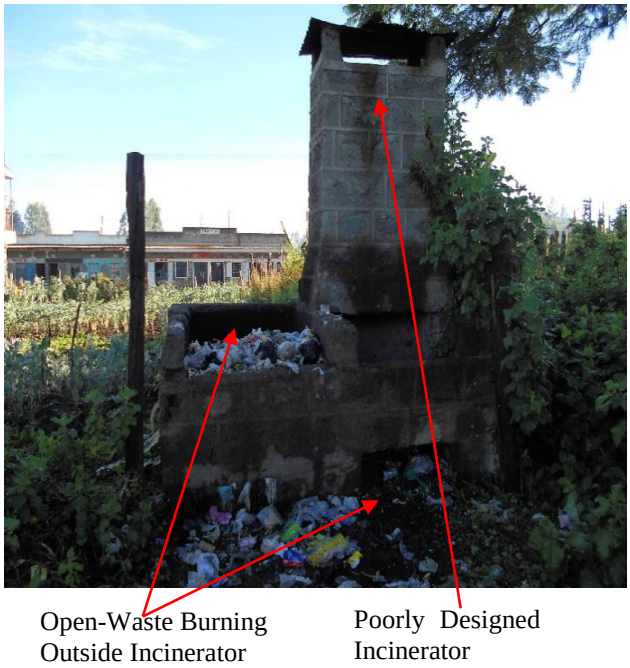

Figure 3.5: A non-performing small scale incinerator.

a) Carbon monoxide

The imperfect waste mixing would allow CO to escape from incinerator due to blockages of air inlet ports and combustion chamber overloading. Even in premixed combustion systems, CO levels would be relatively high due to high equilibrium concentrations at flame temperature, where the gases are hot prior to ignition. Figure 3.6 shows the CO emission levels when incinerating waste at various incinerator loading rates. Incinerating wastes at loading rates of 45, 30 and 15 kg, yielded mean CO values of 7.7, 5.6 and 3.9 ppm, respectively. The CO emissions increased towards the peaks of 15.6, 12.6 and 10 ppm at loading rates of 45, 30 and 15 kg, respectively at 50th minute. The results of the 45 kg loading rate agreed with the findings by [24] in which waste incineration yielded mean CO emissions ranging from 7.5 to 9 ppm. The results differed with the findings by [17] that CO emission concentration at the flue gas amounted to 94 ppm at 950ºC for municipal sewage sludge large scale incinerator. Quina *et al.*, (2011) [8] noted that the increase of CO and volatile organic compounds content in the flue gases was a strong indication of furnace inappropriate burning conditions which would be adjusted by increasing of raw air inlet, pressure below the grid and reducing flue gas recycling at the furnace.

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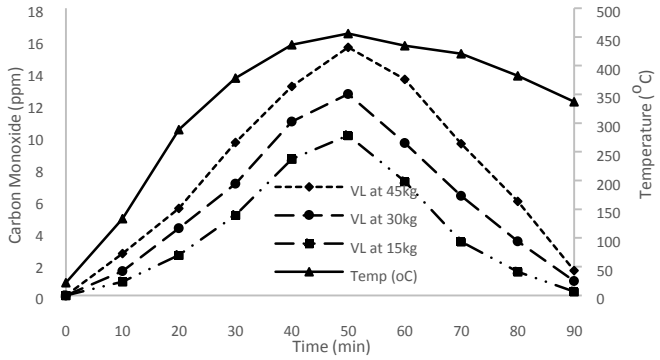

Figure 3.6: Carbon monoxide at varying loading rate.

b) Carbon dioxide

The CO_2 emission was higher at low temperatures due to the released carboxyl at those temperatures while CO and HC were produced instead of CO_2 as the temperature increases due to secondary cracking of volatile matters. Figure 3.7 shows the CO_2 emission levels when incinerating solid waste at different incinerator loading rates. Waste incineration at loading rates of 45, 30 and 15kg yielded mean CO_2 emissions of 10.1, 7.5 and 5.7%, respectively. The CO_2 emission increased gradually to maxima 18.9, 14.6 and 12.5% from loading rates of 45, 30 and 15 kg, respectively. The results agreed with the report by [18] that waste incineration yielded mean CO_2 emissions ranging from 8 to 12.7% in the United State between the year 2005 and 2011. However, the results disagreed with the report by [17] that CO_2 emissions concentration from the coal mono-combustion furnace flue gas yielded mean 11.36% at 950ºC setting. The results also disagreed with the report by [10] that CO_2 emissions from small-scale medical waste incinerators in South Africa yielded mean value of 5.4%. The higher the CO_2 emission levels the more efficient are the operating processes. Therefore, air/waste imbalances, misfires, or poor design and mechanical problems may cause CO_2 to decrease.

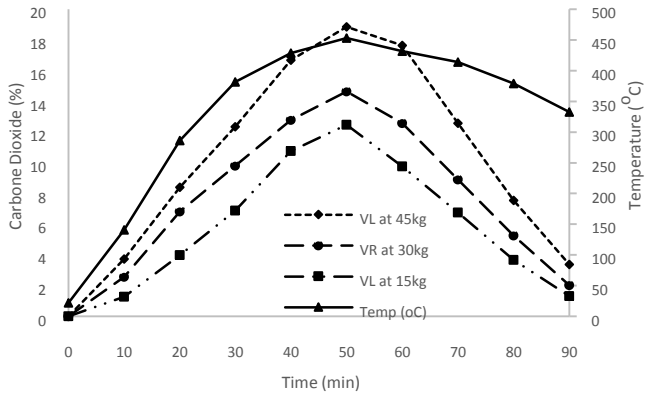

Figure 3.7: Carbon dioxide at varying loading rate.

c) Hydrocarbon

The presence of hydrocarbon (HC) emissions in flue gases is a strong indication of incomplete combustion. Figure 3.8 shows the hydrocarbon emission levels when incinerating waste at various incinerator loading rates. Waste incineration at loading rate of 45, 30 and 15 kg yielded HC emissions of 945, 720 and 577 ppm, respectively. The HC emissions increased towards maximum of 1701, 1435 and 1182 ppm for incinerator loading rate of 45, 30 and 15 kg, respectively at 50th minute after which it decreased gradually. The results differed with the report by [25], that the total polycyclic aromatic hydrocarbons concentrations at the stack of the fixed grate medical waste incinerator was 856000 μg/kg or 856 ppm and that of mechanical grate medical waste incinerator was 252000 μg/kg or 252 ppm. The cause of the differences may be due to that the incinerator used had Air Pollution Control Devices and the wastes in the study contained high percentages of polythene papers. The cause of the differences may be due to the incinerator used was a medical waste large scale type. Since a hydrogen atom has higher affinity to oxygen than a carbon atom, some of the HC would oxidize to hydrogen and water hence reducing the overall HC levels in the exhaust gases at higher temperatures. Pollutants such as polyaromatric hydrocarbon (PAH), ethylene and benzene have carcinogenic and mutagenic properties [26]. The release of HC emissions from incineration processes should be minimized.

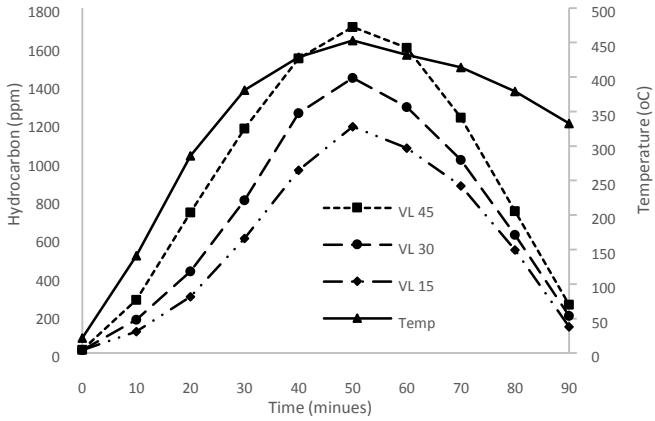

Figure 3.8: Hydrocarbon at varying incinerator loading rate.

d) Oxygen depletion

Figure 3.9 shows the oxygen depletion levels when incinerating waste at different loading rates. Waste incineration at various loading rates of 45, 35 and 15 kg yielded mean oxygen depletion levels of 10.2, 12.0 and 13.9%, respectively.The oxygen levels decreased with time towards minimum values of 2.7, 4.1 and 6.4% at loading rates of 45, 35 and 15 kg, respectively at 50th minute after which it increased gradually. The temperature increased with time from 23ºC towards maximum of 456ºC due the heat produced by burning waste. The increase in oxygen depletions was due to the chemical reaction with CO forming CO_2, carbon to CO_2, HC to steam (H_2O) and CO_2 during waste incineration [27]. The results differed with the report by [17] that oxygen depletion levels concentration from municipal sewage sludge mono-combustion furnace at the flue gas yielded 15.2% at 950ºC.

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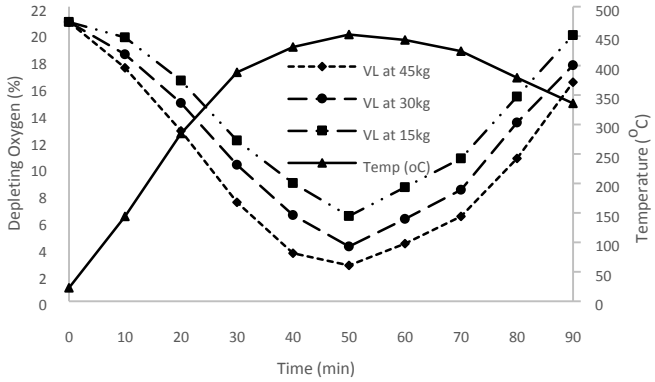

Figure 3.9: Oxygen depletion at various loading rates.

3.2.3 Emissions from various waste types incineration

In this section various waste types/categories were incinerated and their emissions analyzed. The various waste categories included domestic/Residential, agricultural, institutional/industrial and commercial. The institutional waste yielded the highest emission levels followed by commercial which was comparable to municipal solid waste. Table 3.3 in the appendix shows the emission levels when incinerating various types/categories of solid wastes.

a) Carbon Monoxide

The presence of carbon monoxide (CO), describes the combustion efficiency, which also indicates the formation of other products of incomplete combustion.The excess air would greatly lower the formation of CO by allowing it to react with O_2 forming CO_2 which would be oxidized if sufficient air was mixed with gases at high temperatures. Figure 3.10 shows the CO emission levels when incinerating various categories of wastes. The various waste categories incineration, comprising of domestic, agricultural, institutional and commercial yielded the mean CO emissions of 6.5, 8.6, 13.0 and 10.6 ppm, respectively. The CO emissions increased with time towards maximum values of 16.8, 21.4, 30.2 and 24.5 ppm from domestic, agricultural, institutional and commercial, respectively at the 60th minute. The results agreed with the report by European Union standards for small-scale incinerator which should not exceed 40 ppm by volume [9]. The results disagree with the report by [28] that the incineration of a novel four chambers infectious meat incinerator yielded mean CO emission of 32.1mg/m^3 or 28.03 ppm. The results also differed with the report by [17] that CO emissions concentration at the flue gas amounted to 508 ppm at 950ºC for coal-mono combustion furnace. The differences were due to the fact that the incinerators used were small scale compare with those from the literature which were of large scale.

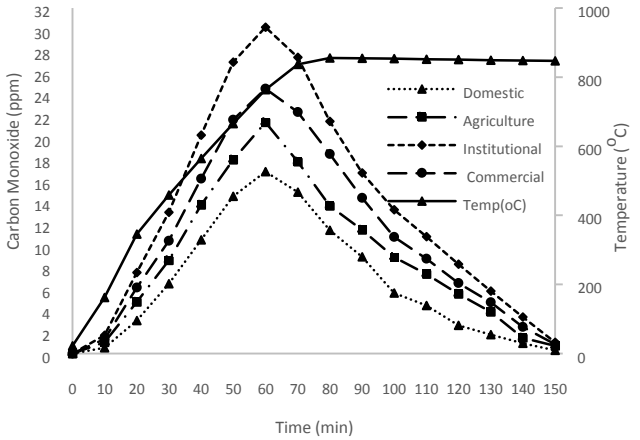

Figure 3.10: Carbon monoxide from different types of waste.

b) Carbon Dioxide

Figure 3.11 shows the carbon dioxide (CO_2) emission levels from various waste categories incineration. When incinerating domestic, agricultural, institutional and commercial wastes, it yielded mean CO_2 emissions of 6.4, 8, 12.4 and 9.7%, respectively. The CO_2 emission levels increased with time towards maximum values of 14.5, 17.4, 24.9 and 20.2% from domestic, agricultural, institutional and commercial waste, respectively. The results disagreed with the report by [29] that the CO_2 emissions from waste incineration in the United State accounted for 14.9% in 2009.The results also disagreed with the report by [17] that CO_2 emission concentration of flue gas amounted to 8.9% at 950ºC for municipal sewage sludge and coal co-combustion furnace. The results also differed with the report by [30] that the incineration from a plasma reactor without the Air Pollution Control Devices (APCD) yielded mean CO_2 of 18.4%.

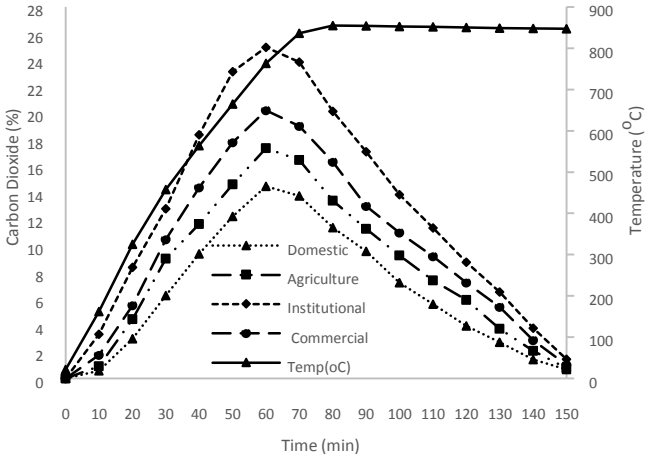

Figure 3.11: Carbon dioxide emissions at various waste types.

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c) Oxygen depletion

Figure 3.12 shows the oxygen depletion levels when incinerating various categories of waste. The incineration of various categories of waste consisting of domestic, agricultural, institutional and commercial yielded mean oxygen (O_2) depletion levels of 15.1, 13.7, 9.1 and 10.6%, respectively. The oxygen decreased with time toward minima of 7, 5.4, 2.1 and 3.6 % when incinerating domestic, agricultural, institutional and commercial waste, respectively at the 60th minute. The institutional waste results agreed with the report by [17] that O_2 depletion levels concentration in the flue gases amounted to 9.2% at 950^{o}C for coal mono-combustion furnace. The reduction in combustion efficiency, would result to some of waste not burned and oxygen unutilized hence increasing the oxygen content in the flue gases. If the air/waste ratio would be chemically correct and the combustion process efficient, oxygen depletions would be reduced to almost zero.

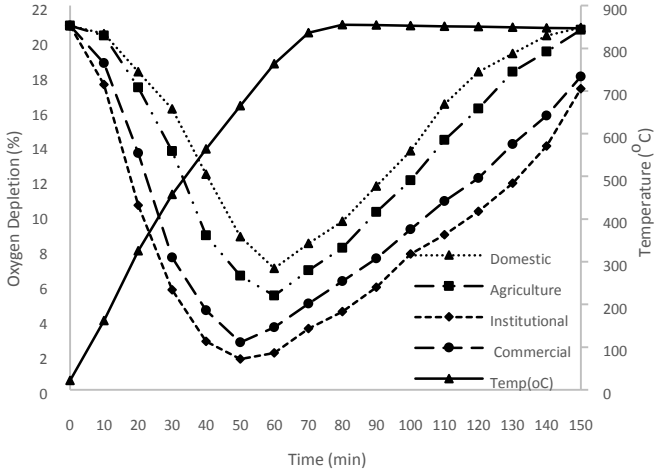

Figure 3.12: Oxygen depletions at various waste categories.

d) Hydrocarbon

The hydrocarbon (HC) emissions from waste incineration contributed to about 10% of the total atmospheric pollutions [17]. Figure 3.13 shows the hydrocarbon emission levels when incinerating various categories of waste. The incineration of domestic, agricultural, institutional and commercial waste yielded mean HC emissions of 671, 869, 1244 and 1095 ppm, respectively. The hydrocarbon emissions increased with time towards maximum values of 1434, 1717, 2201 and 2049 ppm from incineration of domestic, agricultural, institutional and commercial waste, respectively at the 60th minute. The results differed with the report by [23] that the maximum HC emission concentrations of solid waste incineration from two-stage combustion incinerator yielded 1970 ppm at the 90th minute. A rich mixture (excess waste or lack of oxygen) would result in high levels of HC due to insufficient oxygen to combine with hydrogen and carbon, forming steam and carbon dioxide during combustion processes. Excessively weak mixtures would also result in high HC emissions as weak mixtures cannot support complete combustion within the combustion chamber. The amounts of HC and CO on the grate bed increased slightly in the downstream part of the bed, where the air/waste gas turbulence and combustion of the remaining char progressed rapidly [21].

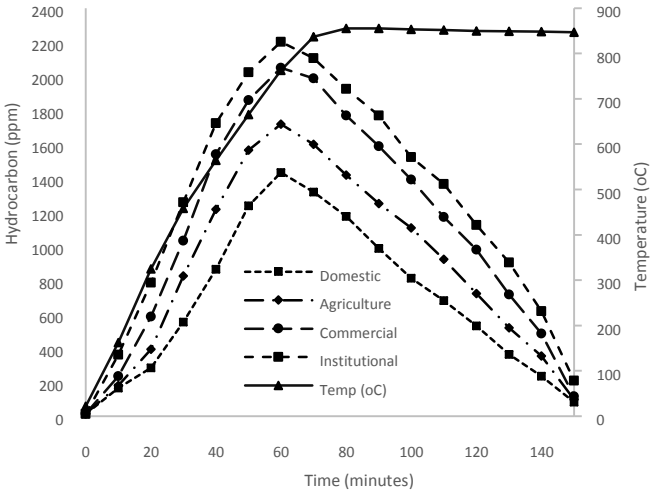

Figure 3.13: Hydrocarbon emissions at various waste categories.

3.2.4 Emissions at varying operating temperatures

The incinerator operating temperature settings used were 450, 650 and 850^{o}C. Quina *et al.*, (2011) [8] and Bradfield, (2014) [31] reported that the European legislation imposed a minimum gas phase combustion temperature of 850^{o}C and the residence time of at least 2 seconds. Table 3.4 in the appendix shows emission levels of carbon monoxide, carbon dioxide and hydrocarbon and oxygen depletion levels when incinerating waste at varying operating temperature settings.

a) Carbon monoxide

The carbon monoxide (CO) is formed due to insufficient combustion air, poor mixing and low flame temperature. Figure 3.14 shows the carbon monoxide emission levels when incinerating waste at various incinerator operating temperatures. Waste incineration at varying operating temperature settings of 850, 650 and 450^{o}C yielded mean CO emissions of 5.7, 7.8 and 10.0ppm, respectively. The CO emissions increased with time toward maxima of 13.2, 16.3 and 18.6 ppm at operating temperatures of 850, 650 and 450^{o}C, respectively at the 60th minute. The results agree with the report by [8] that the mean CO emissions from waste incineration before the flue gas treatment ranged from 5 to 50 mg/m^3 (4.37 to 43.67 ppm). However, these results disagreed with the findings reported by [17] that the CO emissions concentration in the flue gases amounted to 238 ppm at 950^{o}C for municipal sewage sludge and coal co-combustion furnace. The incinerators should work at higher temperatures in order to reduce the emissions.

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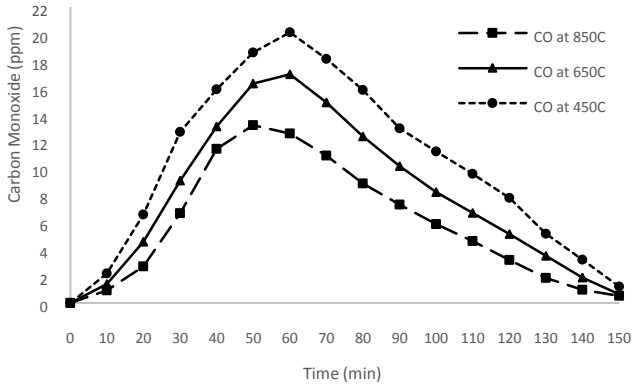

Figure 3.14: Carbon monoxide at varying operating temperatures.

b) Carbon dioxide

The higher combustion air would dilute the flue gases causing the carbon dioxide (CO_2) concentration to drop where the maximum value depends upon the type of waste used. Figure 3.15 shows carbon dioxide emission levels when incinerating waste at various operating temperature settings. The waste incineration at operating temperatures of 850, 450 and 650ºC yielded mean CO_2 emissions of 7.2, 9.4 and 12.0%, respectively. The CO_2 emissions increased with time towards the maximum values of 15.6, 18.1 and 22.3%, at furnace operating temperatures of 850, 650 and 450ºC, respectively at the 50th minute. The results due to 450ºC operating temperature agreed with report by [32] that the Canada's total CO_2 emission levels from waste incineration amounted to 12% in 2011. These results disagreed with the report by [33] that the CO_2 emissions at primary chamber temperature fixed at 400ºC ranged from 4.2% to 9.2% from the fixed-bed incinerator at Bagamoyo in Tanzania. These results also disagreed with the mean CO_2 emissions of 5.4% from small-scale medical waste incinerators in South Africa as reported by [10]. Mohareb *et al.*, (2008) [34] noted that before the waste left the grate, most of the volatile component had oxidized into carbon dioxide and steam (H_2O), though some oxidized into carbon monoxide and hydrocarbons.

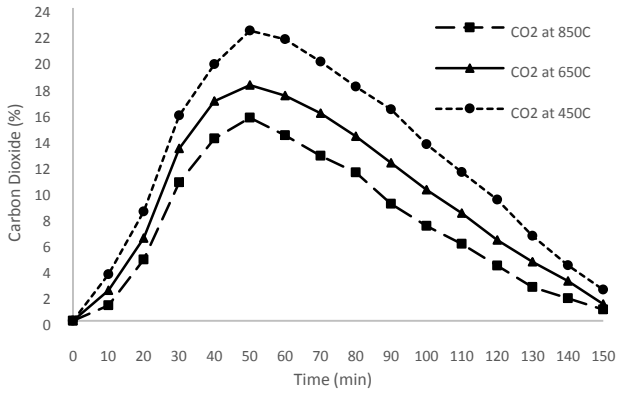

Figure 3.15: Carbon dioxide at varying operating temperature.

c) Hydrocarbon

The hydrocarbon (HC) emissions from incineration facilities were mainly as a result of bad waste to air mixing ratios, lower operating temperatures forming cold spots in the combustion chamber and high MC. Figure 3.16 shows the hydrocarbon emission levels when incinerating wastes at varying operating temperatures. The waste incineration at varying operating temperatures of 850, 650 and 450ºC yielded mean HC emissions of 644, 855 and 1293 ppm, respectively. The HC emissions increased with time towards maximum values of 1468, 1763 and 2483 ppm at varying operating temperatures of 850, 650 and 450ºC, respectively at the 60th minute. The results disagreed with the findings by [35] that the mean HC emissions from different wastes incinerators at 850ºC ranged from 4376 to 117740 mg/kg (4376 to 117740 ppm). Under the furnace conditions chlorine and fluorine would be converted into acid hydrogen halides and hydrocarbon, part of which would react to form metal chlorides. The HC emissions were considered to be potential health hazard due to its immunotoxicity, genotoxicity, carcinogenicity, reproductive toxicity properties [6].

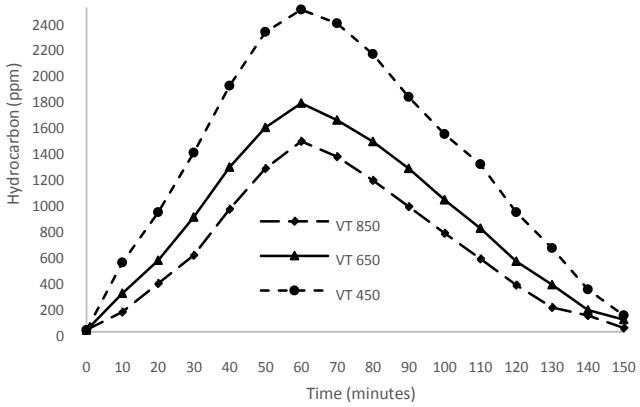

Figure 3.16: Hydrocarbon at varying operating temperature.

d) Oxygen depletion levels

The concentration of carbon monoxide molecules decreases rapidly with increase in air levels as they pick up additional oxygen (O_2) atoms and form carbon dioxide (CO_2). Figure 3.17 shows oxygen depletion levels when incinerating waste at various operating temperatures. Waste incineration at operating temperatures of 850, 650 and 450ºC yielded mean oxygen depletion levels of 13.7, 12.7 and 10.6%, respectively. The oxygen decreased with time toward minima of 2.4, 4.8 and 5.9% at operating temperatures of 850, 650 and 450ºC, respectively at the 50th minute. As the combustion processes propagates further into the grate bed, the gas temperature gradually decreases. The results at 450ºC operating temperature agreed with the report by [32] that the oxygen depletions at primary chamber with temperature set at 400ºC ranged from 8.8 to 12.2% for the fixed-bed incinerator at Bagamoyo in Tanzania. The results disagreed with the report by [24] that the waste incineration operations yielded mean O_2 depletion levels ranged from 7.2 to 9.1%.

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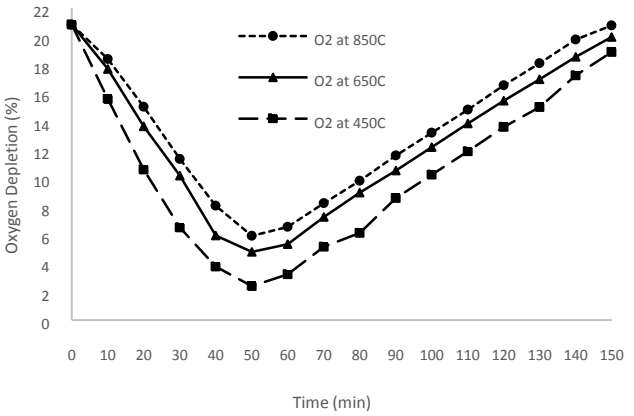

Figure 3.17: Oxygen depletions at various temperatures.

3.3 Smoke Density and Bottom Ash

Smoke density and incinerator bottom ash are measures of incineration performance. The residence time, distribution of different flue-gas streams and the in-flight time distribution of each incoming stream would ascertain the combustion status. The turbulence of the combustion air and waste vapour determines the incineration processes. The waste contained large percentage of volatiles matters which resulted in production of large quantities of tar during incineration. The tar fell onto the grate and cracked into char and non-condensable gases while others were combusted to provide heat in order to sustain the incineration process [36].

3.3.1 Smoke density

The smoke density is the visible suspension of carbon or other particles in the air emitted from burning of any combustible materials. The smoke opacity provides an indirect measurement of particulate matter concentration in the stack/chimney. Specific smoke density provided estimates of particulate matter and the combustion pattern, estimated based on the burning conditions [10]. Figure 3.18 shows the dark and dense smoke with excessive particulate matter emissions from the small-scale incinerator at Community Resource Center opposite Njoro cunning factory. Visual observation was used to note the combustion performance and gross changes in the stack flue gas opacity could be detected as noted by [9]. The smoke density was relatively high for institutional waste, followed by commercial and domestic while agricultural waste yielded the lowest. The institutional waste contain synthetic resins plus polythene papers, plastic and rubber which would ignite easily reaching the maximum smoke density quickly and emitted large amounts of fine particulates within a short time.

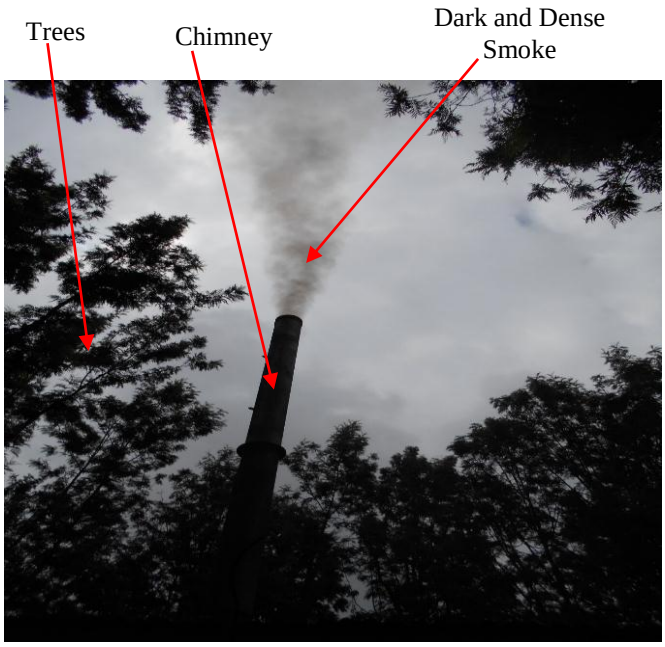

Figure 3.18: Dark and dense smoke with particulate matter.

3.3.2 Bottom ash

The shutdown of the incinerator initiated the cool-down period which was determined by a pre-set length of time into the cycle, lasting for ten hours. The bottom ash and combustion chamber was not sprayed with water to fasten the cooling process because rapid cooling would adversely affect the refractory. Figure 3.19 shows bottom ash residues from various waste incineration experiments. The results indicated that waste with high percentage of plastic blends and agglomerate revealed burnt and sintered surface whereas the inside remains unburned, because plastic materials would melt from surface to core due to low thermal conductivity and had problems of the ‘‘sticky phase’’ as reported by [37]. The physical and chemical properties of the incinerated bottom ash vary depending on the type and source of the solid waste [38]. Bottom ash containing large pieces of unburned material (other than material which were not combustible such as glass, cans and pieces of metal) showed poor incinerator performance. It would be necessary to return those pieces of waste into the incinerator to be burned again. Ash colour was also an indicator of ash quality. White or greyish ash indicated that a low percentage of carbon remained in the ash. Black ash indicated high percentages of carbon remaining in ash showing that the combustion was not complete [11]. Bottom ash containing slag, glasses and partially unburned organic matter were generally coarse sandy in appearance. Fly ash consisted of partially burned organic matter and its dust-like grey particles. Equations 2.3 and 2.4 were used for determination of bottom ash.

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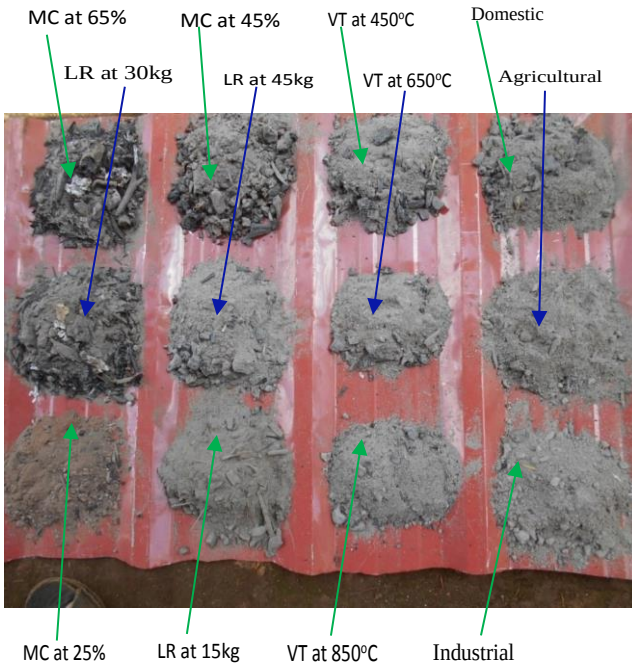

Key: MC-Moisture Content; LR-Loading Rate and VT-Incinerator Varying Temperature.

Figure 3.19: Bottom ash residues from different experiments.

4. CONCLUSIONS

Solid waste incineration reduces weight, volume, and odour which also results in emissions of flue gases and other residues like the bottom ash and fly ash. The emissions and pollutants of concern from waste incineration were carbon monoxide, carbon dioxide, hydrocarbon, oxygen depletion levels, smoke density and bottom ash residues. The study determined the influence of Moisture Content (MC), incinerator loading rate, operating temperatures and waste categories on incineration performance and emission levels. High MC required longer drying time, more heat energy, lowered operating temperatures in the furnace and vice versa. Higher MC resulted to higher flue gas emissions which had direct effects on smoke density and bottom ash quality. The reduction of MC of waste before loading it into the combustion chamber, resulted in more stable ignition conditions, increased efficiency and improved incineration performance.

Incinerating waste at various loading rates had a direct impact on flue gases, smoke density and bottom ash quality. Overloading the incinerator caused blockage of air ports to the combustion chamber, poor waste-to-air ratios, high emissions, high smoke density and unburnt remains on bottom ash leading to poor incineration performance. The underloading of the incinerator increased waste burning rate, gas velocities and the amount of fly ash in the flue gases. High operating temperatures and holding times led to complete combustion of hydrocarbon materials in the waste, non-combustible ash, low concentration of smoke density and flue gases. The turbulent mixing of carbon monoxide and hydrocarbon with adequate oxygen promoted good contact between the burning waste and incoming air enabling high temperatures to be achieved for complete combustion.

The evolution of smoke, prolonged burning time and intensity varied with the type of waste. High levels of hydrocarbon emissions and flue gases from Industrial and commercial waste was an indication of high percentage of polythene papers, plastics, rubber, fluorinated textiles, inorganic chlorides and fluorides in the waste. Dark and dense smoke with particulate matter concentration indicated incomplete combustion of waste due to incinerator overloading, high MC in the waste, low operating temperatures and poor air-waste ratios. The consistence of fine grey bottom ash in the furnace was an evaluation tool for good incineration performance.

A well-controlled combustion process maintains low emissions of harmful gases and provides the highest combustion efficiency. Also, a carefully-designed furnace leads to improved fuel system and air circulation, well-mixed waste with low moisture content, high operating temperatures, better incinerator loading rates and reduced emissions of flue gases.

REFERENCES

[1] Manyele, S. and Kagonji, I. (2012). Assessment of incineration process performance in a district hospital using statistical analysis. *Scientific Engineering Research Journal, 4: 421-434.*

[2] Lombardi, F., Lategano, E., Cordiner, S. and Torretta, V. (2013). Waste incineration in rotary kilns: A new simulation combustion tool to support design and technical change. *Journal of Waste Management & Research, pp 1-12.*

[3] ENVILEAD, (Environmental Liaison, Education and Action for Development) (2005). Waste incineration activities in Nairobi that release dioxin and furan into the environment. *International POPs Elimination Project* (IPEP), Nairobi, Kenya.

[4] Belliveau, M. and Lester, S. (2004). PVC bad news comes in: The poison plastic, health hazards and the looming waste crisis. *The Center for Health, Environment and Justice*, Falls Church, Virginia.

[5] Tangri, N. (2003), Waste Incineration: A Dying Technology: Essential Action for Gaia.

[6] Lewtas J. (2007). Air pollution combustion emissions: Characterization of causative agents and mechanisms associated with cancer, reproductive, and cardiovascular effects. *Science Direct* pp. 95-133.

[7] Park, Y., Kim, W. and Jo, Y. (2013). Release of Harmful Air Pollutants from Open Burning of Domestic Municipal Solid Wastes in a Metropolitan Area of Korea. *Aerosol And Air Quality Research Journal*, Taiwan. 13:1365–1372.

[8] Quina, M., Bordado, J. and Quinta-Ferreira, R. (2011). Air pollution control in municipal solid waste incinerators. *The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources*, pp 331-358.

[9] Batterman, S. (2004). Assessment of small-scale incinerators for health care wastes. Water, sanitation and health protection of the human environment under world health organization. *Geneva 27, Switzerland.*

[10] Rogers, D. and Brent, A. (2006). Small-scale medical waste incinerators – experiences and trials in South Africa. *Council for Scientific and Industrial Research Pretoria, South Africa.*

[11] Guendehou, G., Koch, M., Hockstad, L., Pipatti, R. and Yamada, M. (2006). Incineration and open burning of waste. IPCC Guidelines for National Greenhouse Gas Inventories. U.S.A.

[12] Chen, T. and Lin, C. (2010). CO_2 emission from municipal solid waste incinerator: IPCC formula estimation and flue gas measurement.. *Journey of Environmental Engineering and Management.* Taipei 106, Taiwan.

[13] Ujam, A. and Eboh, F. (2012). Flue gas analysis of a small-scale municipal solid waste-fired Steam generator. *International Journal of Computational Engineering Research, 2* (8): 8-20.

[14] El-Mahallawy, F. and Habik, S. E. (2002). Fundamentals and Technology of Combustion. *Elsevier Science*, Amsterdam U.K.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 03, March-2017

[15] Ujam A., Eboh F. and Chime T. (2013). Effective utilization of a small-scale municipal solid waste for power generation. *Journal of Asian Scientific Research*, 3(1): 18-34.

[16] Macknick, J. (2011). Energy and CO2 emission data uncertainties. Future Science Group publishers, *Journey of Carbon Management*, *2*(2):189-205.

[17] Chen, W., Han, J., Qin, L., Furuuchi, M. and Mitsuhiko, H. (2014). The emission characteristics of PAHs during coal and sewage sludge co-combustion in a drop tube furnace. *Journal of Aerosol and Air Quality Research*, *14*:1160–1167.

[18] USCAR, (U.S. Climate Action Report), (2014). Greenhouse Gas Inventory. Climate Action Report. U.S.

[19] Botter, D., Jorgensen, B. and Peres, A. (2002). Longitudinal study of mortality and air pollution for Sao Paulo, Brazil. *Journal of Exposure Analysis and Environmental*, 12: 335-343.

[20] Carson, P. and Mumford, C. (2002). Hazardous chemicals handbook, 2nd edition. Butterworth-Heinemann, London, Great Britain.

[21] Liu, K., Han, W., Pan, W. and Riley, J. (2001). Polycyclic Aromatic Hydrocarbon (PAH) emissions from a coal-fired pilot FBC system. *Journal of Hazardous Materials* pp: 175–188.

[22] Dyke, P. (2002). Polychlorinated biphenyls (PCB) and polycyclic aromatic hydrocarbons (PAH) Releases from incineration and power generation processes. *Environment Agency*, Bristol.

[23] Saeed, L. (2004). Experimental assessment of two-stage combustion of high PVC solid waste with HCL recovery. PhD Dissertation in Mechanical Engineering Helsinki University of Technology.

[24] Astrup, T., Riber, C. and Pedersen, A. (2011). Incinerator performance: effects of changes in waste input and furnace operation on air emissions and residues. *Waste Management & Research*, pp 1-12.

[25] Lee, W., Liow, M., Tsai, P. and Hsieh, L. (2001). Emission of polycyclic aromatic hydrocarbons from medical waste incinerators. *Atmospheric Environment*, 36: 781–790.

[26] Banar, M., Cokaygil, Z. and Ozkan, A. (2009). Life cycle assessment of solid waste management options for Eskisehir, Turkey.

[27] Whitworth, A. (2005). Part I. Thermal Breakdown Characteristics of Municipal Solid Waste Components in varying Oxygen Environments and Part II. Municipal Solid Waste Management in China. Columbia University, New York.

[28] Salam, H. (2013). Operating and emission characteristics of a novel design four chambers infectious meat incinerator. *International Journal of Research in Engineering and Technology*, 2(11): 322-328.

[29] USEIA, (U.S. Energy Information Administration), (2011). Emissions of greenhouse gases in the United States 2009. U.S. Department of Energy Washington, DC.

[30] Musale, S. and Padhy,a H. (2013). Process modeling and simulation in plasma technology-An innovative approach towards sustainable solution for solid waste treatment. *International Refereed Journal of Engineering and Science (IRJES)*, 2(4): 50-54.

[31] Bradfield, F. (2014). Examination of the thermal properties of municipal solid waste and the scalability of its pyrolysis. Master of engineering (Chemical Engineering) thesis, Stellenbosch University.

[32] Omari, A. (2015). Characterization of Municipal solid waste for energy recovery. A case study of Arusha, Tanzania. *Journal of Multidisciplinary Engineering Science and Technology, 2* (1): 230-237.

[33] Environment Canada (2013). Canada's Emissions Trends. Minister of the Environment. Canada.

[34] Mohareb, A., Warith ,M. and Diaz, R. (2008). Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, *Canada. Resour. Conserv. Recy*, Ottawa, Ontario, Canada.

[35] Conesa, J., Font, R., Fullana, A., Martın-Gullon, I., Aracil, I., Galvez, A., Molto, J., Gomez-Rico, M. (2008). Comparison between emissions from the pyrolysis and combustion of different wastes. *Journal of Analytical and Applied Pyrolysis*, pp. 1-8.

[36] Ayaa, F., Mtui, P., Banadda, N. and Van Impe, J. (2014). Design and computational fluid dynamic modeling of a municipal solid waste incinerator for Kampala city, Uganda. *American Journal of Energy Engineering*, 2(3): 80-86.

[37] Zhu, J., Chen, L., Fang, J. and Shi, B. (2013). An integrated process investigation of selfsustaining incineration in a novel waste incinerator: Drying, pyrolysis, gasification, and combustion of sludge-plastic blends. *International Journal of Water Resources and Environmental Engineering*, *5*(12): 648-658.

[38] Alhassan, H. and Tanko, A. (2012). Characterization of solid waste incinerator bottom ash and the potential for its use. *International Journal of Engineering Research and Applications (IJERA)*,2 (4): 516-522.

APPENDEX

Table 3.1: Emissions of gases at various moisture contents (MC) of the wastes.

		Carbon Dioxide			Carbon Monoxide			Oxygen Depletion			Hydrocarbon		
Time	**Temp**	**MC 65**	**MC 45**	**MC 25**	**MC 65**	**MC 45**	**MC 25**	**MC 65**	**MC 45**	**MC 25**	**MC 65**	**MC 45**	**MC 25**
0	22	0	0	0	0	0	0	20.8	20.8	20.8	13	12	14
10	163	1.8	0.6	0.4	0.6	0.6	0.4	18.6	20.1	20.3	193	157	145
20	334	9	5.4	2.3	2.9	3.3	2.3	13.4	15.6	16.7	578	426	387
30	437	16.2	9.8	6.5	7.6	6.8	5.4	9.6	10.8	11.7	955	743	621
40	554	22.6	13.8	11.4	12.6	10.3	8.2	6.8	7.8	8.8	1382	1121	875
50	643	24.4	15.1	13.3	14.8	12.7	9.4	4.5	5.9	7.3	1673	1372	1159
60	720	21.9	13.1	10.5	15.4	11.7	9.8	5.2	6.7	8.3	1779	1482	1324
70	802	16.4	10.3	8.9	13.2	10.2	8.1	6.5	8	9.3	1667	1373	1245
80	852	11.9	8.9	7.4	11.8	8.2	6.9	7.9	9.2	10.6	1498	1224	1086
90	855	10	7.6	6.2	8.9	7.1	6	9.2	10.9	12.2	1287	1086	954
100	854	8.5	6.4	5	7.2	5.8	4.8	10.9	12.7	14	1118	905	737
110	853	6.8	5.1	3.6	5.3	4.2	3.3	12.5	14.2	15.2	941	712	567
120	852	5	3.8	2.5	4.4	2.6	2	14.2	16	16.7	729	519	373
130	850	3.2	2.3	1.7	2.7	1.2	0.9	16.3	17.6	18.2	482	313	193
140	849	1.9	1.2	0.9	1.3	0.3	0.2	18.7	19.3	19.9	256	145	115
150	848	0.9	0.5	0.3	0.6	0.2	0.1	20.5	20.7	20.7	111	92	85
Average		**10.0**	**6.5**	**5.1**	**6.8**	**5.3**	**4.2**	**12.2**	**13.5**	**14.4**	**916**	**730**	**618**

Key for Table 3.1
MC: Moisture content (%); Temp: Temperature (oC)

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Table 3.2: Emissions of gases at various incinerator loading rates.

		Carbon Dioxide			Carbon Monoxide			Hydrocarbon			Oxygen Depletion		
Tim	Temp	VL 45	VL 30	VL 15	VL 45	VL 30	VL 15	VL 45	VL 30	VL 15	VL 45	VL 30	VL 15
0	22	0	0	0	0	0	0	13	11	12	20.8	20.8	20.8
10	141	3.7	2.6	1.3	2.6	1.5	0.9	278	175	113	17.4	18.4	19.7
20	286	8.4	6.8	4	5.5	4.2	2.5	784	426	295	12.7	14.8	16.5
30	381	12.3	9.8	6.9	9.6	7	5	1261	797	598	7.4	10.2	12
40	429	16.7	12.7	10.8	13.1	10.9	8.5	1537	1252	954	3.6	6.4	8.8
50	453	18.9	14.6	12.5	15.6	12.6	10	1701	1435	1182	2.7	4.1	6.4
60	432	17.6	12.6	9.8	13.6	9.6	7.1	1582	1284	1069	4.3	6.1	8.5
70	414	12.6	7.9	6.8	9.5	6.2	3.4	1279	1007	872	6.3	8.3	10.7
80	379	7.6	5.3	3.7	5.9	3.4	1.5	761	617	539	10.7	13.3	15.3
90	333	3.4	2	1.3	1.6	0.9	0.2	253	194	137	16.3	17.6	19.9
Average		10.1	7.5	5.7	7.7	5.6	3.9	945	720	577	10.2	12	13.9

Key for Table 3.2
where VL: Varying incinerator loading rates (kg); Temp: Temperature (oC)

Table 3.3: Emission of gases due to incineration of various types of waste.

		Carbon Monoxide				Carbon Dioxide				Hydrocarbon				Oxygen			
Time	Temp	Dom	Agri	Inst	Com	Dom	Agri	Inst	Com	Dom	Agri	Insti	Com	Dom	Agri	Inst	Com
0	22	0	0	0	0	0	0	0	0	13	14	13	14	20.9	20.9	20.9	20.9
10	162	0.5	1	1.7	1.3	0.6	0.9	3.3	1.8	166	181	362	236	20.4	20.3	17.5	18.7
20	345	3.1	4.8	7.5	6.1	3	4.5	8.4	5.5	284	394	785	586	18.2	17.3	10.6	13.6
30	458	6.5	8.6	13.1	10.4	6.2	9	12.8	10.5	553	825	1258	1031	16.1	13.7	5.7	7.6
40	564	10.5	13.8	20.2	16.2	9.4	11.6	18.4	14.4	865	1216	1724	1541	12.3	8.8	2.8	4.5
50	665	14.6	17.9	27	21.6	12.2	14.6	23.1	17.8	1237	1565	2023	1859	8.8	6.5	1.8	2.7
60	763	16.8	21.4	30.2	24.5	14.5	17.4	25	20.2	1434	1717	2201	2049	7	5.4	2.1	3.6
70	837	14.9	17.8	27.4	22.4	13.8	16.5	23.9	19	1319	1598	2106	1987	8.4	6.8	3.5	4.9
80	855	12.4	13.7	21.5	18.5	11.4	13.4	20.2	16.3	1176	1419	1924	1768	9.7	8.1	4.5	6.2
90	855	8.9	11.5	16.7	14.4	9.6	11.3	17.1	13	986	1251	1768	1587	11.7	10.2	5.9	7.5
100	853	5.6	8.9	13.3	10.8	7.2	9.3	13.9	11	812	1108	1524	1391	13.7	12	7.8	9.2
110	852	4.5	7.4	10.8	8.8	5.6	7.4	11.4	9.2	679	923	1365	1171	16.4	14.3	8.9	10.8
120	850	2.6	5.5	8.3	6.5	4	5.9	8.8	7.2	530	721	1124	979	18.2	16.1	10.2	12.1
130	849	1.7	3.8	5.8	4.7	2.7	3.7	6.5	5.4	363	519	903	715	19.3	18.2	11.8	14.1
140	848	0.9	1.4	3.4	2.5	1.4	2.1	3.8	2.9	236	353	618	485	20.3	19.4	14	15.7
150	847	0.3	0.7	1	0.9	0.7	0.8	1.4	1	82	98	208	117	20.7	20.6	17.2	17.9
Average		6.5	8.6	13	10.6	6.4	8	12.4	9.7	671	869	1244	1095	15.1	13.7	9.1	10.6

Key for Table 3.3

Dom: Domestic waste; Agri: Agricultural waste; Inst: Institutional waste; Com: Commercial waste.

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Table 3.4: Emissions of gases at various incinerator-operating temperatures.

	Carbon Dioxide			Carbon Monoxide			Hydrocarbon			Oxygen		
Time	VT 850	VT 650	VT 450	VT 850	VT 650	VT 450	VT 850	VT 650	VT 450	VT 850	VT 650	VT 450
0	0	0	0	0	0	0	14	12	13	20.8	20.8	20.8
10	1.2	2.3	3.3	0.9	1.4	2.2	154	296	534	18.4	17.7	15.6
20	4.7	6.3	8.2	2.7	4.5	6.6	372	551	920	15	13.7	10.6
30	10.6	13.2	15.6	6.7	9.1	12.7	590	883	1380	11.4	10.2	6.5
40	14	16.9	18.7	11.5	13.1	15.9	945	1269	1896	8.1	6	3.8
50	15.6	18.1	21.8	13.2	16.3	18.6	1258	1574	2311	5.9	4.8	2.4
60	14.2	16.8	23.4	12.6	17	20.1	1468	1763	2483	6.6	5.3	3.2
70	12.7	14.9	21.9	11	14.9	18.1	1349	1632	2376	8.2	7.3	5.2
80	11.4	13.3	19	8.9	12.4	15.8	1168	1465	2140	9.8	9	6.1
90	9	12.1	16.2	7.3	10.2	13	964	1259	1809	11.6	10.5	8.6
100	7.3	10.1	13.5	5.9	8.2	11.3	761	1017	1522	13.2	12.2	10.3
110	5.9	8.3	11.4	4.6	6.7	9.6	563	797	1292	14.8	13.9	11.9
120	4.2	6.2	9.4	3.2	5.1	7.8	360	543	921	16.6	15.5	13.6
130	2.6	4.5	6.5	1.9	3.5	5.2	189	364	645	18.1	17	15
140	1.7	3.1	4.2	1.1	1.9	3.2	125	169	325	19.8	18.6	17.3
150	0.9	1.3	2.4	0.5	0.7	1.2	29	93	127	20.8	20	18.9
Average	7.2	9.2	12.2	5.7	7.8	10.1	644	855	1293	13.7	12.7	10.6

Key for Table 3.4
VT: Incenerator operating temperatures (oC)

BIOGRAPH

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