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Development of an Incinerator for Combusting Household Solid Waste

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ABSTRACT

Incineration is the combustion of waste materials at a high temperature environment. It functions as an alternative to landfill and biological treatment methods such as composting process and anaerobic digestion. This work developed a household incinerator for combustion of municipal solid waste. The incinerator consists of a square mild steel box 340 mm x 340 mm, gas burner, grate exhaust and a temperature indicator. The components were designed according to standard engineering procedures and materials selection was based on functionality, durability, cost and local availability with the maximum loading capacity of 2.0 kg of waste. The incinerator was assembled by lining the inner wall of the incinerator with fibre glass of 2 mm thickness after which the temperature indicator was positioned. A rectangular hole of 80 mm x 70 mm was cut from the exhaust at the upper part of the incinerator and rectangular hole of 200 mm x 100 mm was also cut at lower part of two adjacent sides to allow air in the combustion chamber. The developed incinerator was tested using gas as a source of heat. The quantity of heat required for combustion using the developed incinerator for waste paper and plastic were; paper and plastic (combined) 1630.0 kJ, paper1571.14 kJ, and plastic 940.21 kJ. The maximum paper capacity for the incinerator was found to be 2 kg with a burning time of 17 to 18 minutes while that of plastic was 1 kg and the burning time ranged from 20 to 30 minutes. For combination of plastic and paper, it was 1.5 kg and burning time ranged from 17 to 30 minutes. Ash was prevented and kept for further engineering use. In a densely populated area, where finding space for additional landfill was difficult, incinerator made it easier. The developed incinerator was capable of performing the expected function though it is recommended for incineration of low volume of wastes.

1. INTRODUCTION

Waste generation by humans had been an integral part of our civilization since the dawn of history. Transformation of natural resources to meet human needs had always invariably leads to the generation of by-products (Tong and Hu, 2022; Felicia, 2009). As matter existed in three states (solid, liquid and gas), waste also existed in these states. Solid waste is defined as discarded material which has no consumer value to the person abandoning it (Karsauliya, 2013). Generation of solid waste can be from several sources, the main sources being domestic, commercial, industrial, healthcare, agricultural and from mining. The common terms for solid waste includes; garbage, trash, refuse, and rubbish. Solid wastes from domestic activities generally, consist of spoilt or leftover food, plastic most especially from nylon bags and food packages, metals of all types, paper, textile, glass, and electronic waste (Adeboye *et al.,* 2022).

When it comes to generation of wastes, the income level of individual household can affect the level of solid wastes generated. Income determines purchasing power which directly also determines the amount of wastes generated (Jamila, 2018). Low income earners tend to generate lesser amount of waste both in quantity and by composition. Because they usually live in densely packed populated neighborhood, especially in metropolis as compared to high income earner, they have higher solid waste generation per square kilometer of urban space than more affluent areas. While the higher income earners can afford the services of private commercial waste collectors, the low-income earners usually make use of nearby refuse dump which invariably is within the residential areas of the community. In worst cases house backyards are turn to a refuse site by some while others tend to keep their refuse in their houses for a long period before they dispose it.

Available evidence indicated that most environmental, economic and health related problems in human and the environment can be attributed to the incidence of solid wastes (Ozoemene *et al.*, 2014). According to Mueller (2018) domestic waste disposal is an issue that is important to the management of urban areas. Thus, proper management of solid waste is crucial to the overall health of a community. In Nigeria for example, most of the wastes are generated by household, local industries, artisans and traders which litters the immediate surroundings. Improper collection and disposal of municipal wastes which leads to an environmental catastrophe as there is perennial inadequate funding for municipal waste management in government budgetary allocations (Ogundele *et al.,* 2018). In the research work of Adedeji and Amosun (2022a), they mathematically proposed a prognostic model which correlates the relationship between waste management/disposal method and how it affects the people in the vicinity. The model obtained predicts a proportional relationship between appropriate disposal method and the different declined disease out-break. (Tait *et al.,* 2023; Ogundele *et al.,* 2018).

However, solid waste had been suggested as an alternative source of solid fuel. To be useful for this purpose, mechanical as well as combustion properties of the solid waste needed to be determined. Adedeji and Amosun (2022b) determined the mechanical properties of municipal solid waste in Lagos Nigeria using experimental method. The research results showed that green compression, shear strength, permeability builk density and porosity, are functions of moisture content and are useful in landfill design. Furthermore, the research investigated the physical composition and volume of waste for energy recovery possibility. They found out that 35.71% were organic materials that are capable of 21.5828 kJ/kg energy recovery from waste. Adeboye *et al.* (2022) studied wastes plastics using thermogravimetric analysis to investigate their decomposition and pyrolysis behavior. It was conducted that plastic waste can be utilized for energy production. However, despite these promising results on use of waste as an alternative energy source, effective waste management is still a problem, especially in third world countries. In the face of this inadequacy on the side of government, alternatives have been suggested on how to handle the problem of waste management at individuals' level. One of these methods is the use of domestic waste incinerator. The idea behind this suggestion was that incineration reduces the amount of solid waste to be disposed in land fill as well as the fact that incinerated waste posed lesser health risk due to consequential destruction of disease causing microbes (Ezechi, 2017; Narayana, 2009).

An incinerator is a furnace for burning waste. There are various types of incinerator plants designs: moving grate, fixed grate, rotary – kiln, and fluidized bed (Bolaane and Ali, 2004). Incinerator is designed for full oxidative combustion over a general temperature range of 40 - 650^{o} C. This range usually covered the temperature sufficient for melting or calcinations of most solid waste to occur. A typical waste incinerator device usually consists of a combustion chamber, heat source (i.e. gas burner), grill, exhaust chimney and temperature indicators to monitor combustion chamber temperature. In low income countries, landfills and open dumps are still the primary means of disposing waste, however due to poor management as aforementioned they are usually pose health risk to the community hence individual incineration of domestic solid waste should be seen as a palliative to reduce the rate of landfill growth (Berneche-Perez and Sanchez, 2001). Most commercially available portable domestic incinerators are relatively expensive compare to average income in developing countries, this paper therefore aim to present an affordable incinerator incorporating locally available materials for its construction. The developed small scale household incinerator relies on gas to fire and generate the heat needed to raise the temperature of the incinerator to the desired level. It however does not address hazardous and infectious waste.

2. METHODOLOGY

2.1 Description of the Incinerator

The incinerator casing houses all the components of the incinerator including burning chamber, thermocouple, the burner, and exhaust. The size of the burner was utilized in the design of the burner nose inlet. The configuration of the exhaust chimney was made rectangular and attached to a hood in the shape of an inverted hollow square truncated pyramid. The chimney was made long enough to ensure the expulsion of exhaust gases far away from the head level of the user in order ensure the safety of the operator. The exploded and the assembly views of the incinerator is as depicted in Figure 1.

Combustion chamber consists of two concentric square steel hollow boxes with space in-between the boxes filled with fiberglass as insulating material in order to conserve heat and increase burning efficiency in term of fuel consumption. The thickness of the fiberglass infill was determined according to Equation (1). The combustion chamber was provided with two doors. The upper door (of dimension 250 mm by 250 mm) is for loading of refuse to be incinerated, while the lower door (of dimension 150 mm by 300 mm) provided means of getting rid of ashes which are the remnants of the refuse after combustion. The lower end of the combustion chamber also houses the gas burner (standard part) as well as the metal grate to support the refuse during combustion and allows for ashes to pass through (See Figure 1).

Consider a section of the composite wall of the combustion chamber as shown in Figure 2, the thickness of the lagging material was determined through the Fourier's law of heat conduction for a composite wall as represented by Equation (1). Where Q is the quantity of heat that is transferred between the layers of the combustion chamber wall, ti is thickness of the chamber interior steel surface, tf is the thickness of the insulating material, and to is the thickness of the chamber exterior steel surface, k_i is the thermal conductivity of the interior steel surface, k_f is the thermal conductivity of the lagging material, k_o is the thermal conductivity of the exterior steel surface. T_1 and T_4 are temperatures at the chamber's inner steel surface and the outer steel surface respectively. A is the total chamber inner wall surface area (4x30x1855 mm).

$$Q = \frac{A(T_1 - T_4)}{[\frac{t_i}{k_i} + \frac{t_f}{k_f} + \frac{t_o}{k_o}]} \quad (1)$$

The following values were substituted in Equation 1 to determine t_f; t_i = to = 2mm, k_i = k_o = 45Wm-1K-1 (Mild steel), k_f = 0.04Wm-1K-1(fibre glass). T_1 = 300^o C (combustion chamber expected maximum temperature) and T_4 = 23^{o}C (ambient temperature). The mild steel selected for construction has composition of 0.15%C, 0.18%Si, 0.03%S, 0.001P, 0.0005% A, 0.0008% Ni and balance Fe. It was selected for the fabrication of the burning chamber because of its light weight, good strength, weld-ability, available and low cost of purchase.

Chimney and hood closing the top of the combustion chamber is the hood and chimney ensemble. The wider end of the hood directly interfaced with the top of the combustion chamber and help funneled the combustion fume to the chimney which is attached to the hood's smaller upper aperture (See Figure 1). The base is fashioned from a rectangular steel slab and closes the lower end of the combustion chamber. It is provisioned with four metal stands for support. Finally, the combustion chamber was provisioned with a thermocouple temperature probe.

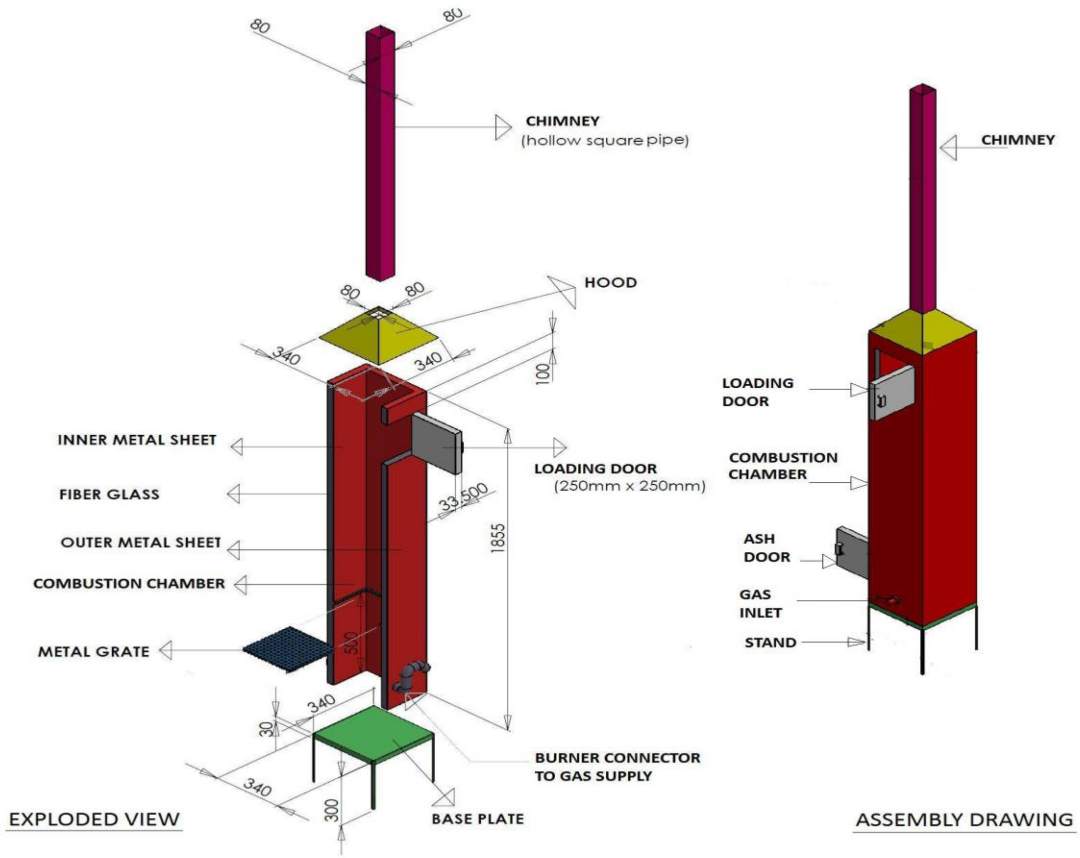

Figure 1: The exploded and assembly views of the developed incinerator

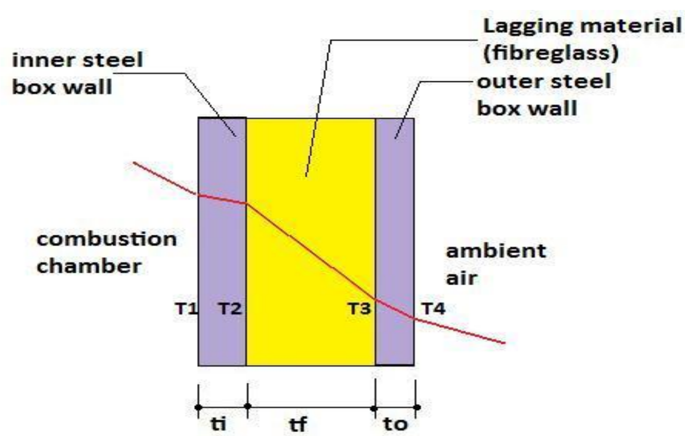

Figure 2: Heat transfer through the combustion chamber composite wall

2.2 Assessment of the Incinerator

The quantity and composition of solid waste to be incinerated was gathered from a building of four (4) families. The solid wastes generated during a period of 30 days from the four (4) families were classified and characterized.

Waste characterization

The method chosen for this study was that used by Bolaane and Ali (2004) *w*hich involves the direct sampling of solid waste from specific sources, a labour intensive manual process of sorting, classifying and weighing all items in each sampling unit and a detailed recording of the data. Generated solid wastes samples were obtained from bins. Each of the waste samples from the source of generation was emptied on a polythene sheet (1meter square) and laid on the bare floor for sorting and weighing. The weight of each waste category was determined and expressed in kilogram. The whole process of sorting and weighing was carried out four times a week. The waste materials were then sorted according to material types which include: paper/cardboard, plastic food pack, plastic bottles, metal cans, food wastes, polythene bags, and other combustion miscellaneous waste materials. Each of these is then weighed to obtain the mass-based characterization.

Evaluation of the machine

The performance of the incinerator was evaluated by considering the functionality and efficiency of the combustion chamber. The thermocouple tip is positioned in the incinerator inner combustion chamber one-third from the base close to the position the waste are burnt. The observation of the thermocouples was done while the combustion is taken place. Incinerator has a high heating rate and the gas or fuel consumption rate is very low. This combustion rate reduces with longer holding time during heat treatment because the design is made to switch off the cylinder once the temperature of the incinerator starts rising.

3. RESULTS AND DISCUSSION

The household size and the mass-based distribution of the characterized waste in different flats of a building is presented in Table (1a and b). It includes the total average waste generated in each flat in kg day^{-1} and the average generation, also in kg day^{-1}, of each characterized waste component. From Table 1b it could be observed that the flat 3 generated the highest mass of waste in the building of study chosen. This is due to the number of people resident in the flat compared to the other selected parts of the flats in this study. The table also shows that food waste constitutes the highest waste component generated in the building (12.98 kgday^{-1}) followed by plastic bottle (10.8kgday^{-1}) and then paper/cardboard (10.7 kgday^{-1}). The Table 2 to 4 show the variation of mass of the waste with time of burning while Tables 2 to 4 indicate energy of burning with temperature at thermometers I and II. By using the knowledge of the average calorific value of waste, mass and duration of burning, the energy of burning could be calculated. Table 2 shows that time of burning of waste paper (sample 1) increases with increase in mass of waste input into the incinerator. When the mass was 0.5kg time taken was 8 minutes while it takes 15 minutes to burn 1kg of wastepaper. The same pattern has been observed from same Table 3 and 4 for samples II and III.

Table 1a: Household Size

Sex	Flat I	Flat II	Flat III	Flat IV	%
Male	2	3	4	4	2.6
Female	1	1	3	2	1.4
Total	3	4	7	6	4

Table 1b: Average Mass- Based Distribution of Solid Waste Material

Site	Paper/ cardboard (kg/day)	Plastic food pack (kg/day)	Metal cans (kg/day)	Food waste (kg/day)	Polythene bag (kg/day)	Plastic bottle (kg/day)	Site total (kg/day)
Flat 1	5.2	0	1.9	0	1.7	3.3	12.1
Flat 2	2	0	0.08	2.58	0.36	2.5	7.46
Flat 3	1.5	2.5	6.1	5.2	2.2	3	20.5
Flat 4	2	1.5	1	5.2	0	2	11.7
Total	10.7	4	9.08	12.98	4.26	10.8	51.76

Table 2: Mass and Incineration Time for Sample I

Mass (kg)	time(t) (mins)
1.5	17
1	15
0.8	13
0.5	8

Table 3: Mass and Incineration Time for Sample II

Mass (kg)	time(t) mins
1	20
0.8	10
0.5	8
0.3	0

Table 4: Mass and Incineration Time for Sample III

Mass (kg)	time(t) (mins)
1.5	17
1	15
0.8	13
0.5	0

Energy of Combustion of Different Sample Wastes

Table 5 shows the energy of combustion with time for sample 1. Since the maximum loading capacity of sample 1 is 2 kg, the quantity of heat at the exhaust was 1397.46 kJ while at the combustion chamber where burning of waste taken place was 1571.14 kJ and the times taken were 15 to 17 minutes respectively. There were no much differences between the time of burning at the chimney and combustion chamber because the paper "sample 1"was arranged evenly and burnt faster. Table 6 shows the energy of combustion with time for sample II. The maximum loading capacity for sample II was 1.5 kg and the quantity of heat at chimney (T_1) was 1449.95 kJ and at combustion chamber (T_2) was 1630.00 kJ. The time taken was 17 mins to 35 minutes respectively. There were many differences between the times of burning due to the presence of plastic because plastic has a lot of chemical composition than paper which are chemically stick together. During the burning, the output contains gaseous liquid, ash, etc. It was observed that another burning took place at the ashing point which really increased the time of burning at the combustion chamber. Table 7 shows the energy of combustion with time for sample III. The maximum loading for sample III was1kg, it contains more spaces. It burnt at 20 to 30 minutes with a quantity of heat of 706.41 kJ to 940.21 kJ respectively. It was observed that despise its small quantity; it still burnt at a very high temperature because of its chemical composition.

Table 5: Energy of Combustion with Time for Sample1"Paper"

T_1(min)	Q_1(kJ)	T_2(min)	Q_2
15	641.28	17	734.8
13	521.04	15	521.04
10	258.84	13	320.64
8	126.92	10	133.6

Table 6: Energy of Combustion with Time for Sample II

T_{i1} (Min)	Q_1 (Kj)	T_{i2} (Min)	Q_2 (Kj)
1	811.6	3	1014
1	511.0	2	631.2
1	360.7	1	493.6
1	210.0	1	270.5

Table 7: Energy of Combustion with Time for Sample III

T_{i1}(min)	Q_1(kJ)	T_{i2}(min)	Q_2(kJ)
20	233.8	30	350.7
10	122.25	12	187.88
8	16.7	9	-25.05
0	-4.18kJ	4	-12.53kJ

Plastics are classified as ordinary combustible and similar to most ordinary combustible such as paper, wool, silk, etc., in that they are capable of thermal degradation with volatile and gaseous products of combustion and have low toxicity. While paper is a versatile material, it burnt about 23^0C, of course many different chemicals could be added to the paper formula to up that temperature, making the paper "flame resistant". During combustion, when all the samples had equal masses their time of burning were not the same, therefore there was a lot of changes and differences in their graphs. Plastic has a very high burning time despite the small quantity of mass it burnt at very longer time compared to other wastes because of its chemical composition which are stick together. The combustion of the plastic at mass 0.25 kg due to the loading capacity of the developed incinerator, showed that there is an initial heat energy (-12.53 kJ) needed to pre-heat the waste before it can start burning. This is due largely to impurities in the plastic and other dirt around the plastic in the waste.

The energy of combustion with mass of waste "paper with plastic" was not the same with that of paper alone and plastic alone. When they have equal of 0.5 kg, the quantity of heat generated for paper, paper with plastic and plastic were 133.6 kJ, 270.54 kJ, -25.05 kg respectively, though it was observed that the higher the mass, the higher the quantity of heat generated. The graph of sample I (paper) was linear, meaning paper burnt faster and the burning is steadily with a by-product of ash, while paper with plastic was linear and quadratic shows that the present of plastic waste caused unsteadily burning, though it burnt but not as faster as when it was only paper, and their by product was ash with a gaseous liquid. During plastic only, the case was completely different. The combustion of plastic, takes longer time and when the mass was 0.25 kg, the quantity of heat generated was so small that the thermocouple at the chimney could not felt the impact, if falls beyond zero level. It was also observed that, there was a plastic drip at the ash door which really increased the time of burning. It was also observed that the readings of the thermocouples are different. The reading at the combustion chamber is different from there adding at the chimney. The thermocouple at the combustion chamber had higher reading than that of the chimney. That was why, the calculation was done separately in order to know the total heat generated at the different point with the mass of waste incinerated.

4. CONCLUSION

The development of a household incinerator using locally sourced materials has being successfully accomplished in this research work, from which the following conclusion could be drawn. The waste characterization identified biodegradable food waste as having the highest average waste characterization of 12.98 $kgday^{-1}$ while discarded plastic bottle, however, exhibit highest quantity of heat 940.21 kJ at 1 kg of mass due to its 22.0 MJ kg^{-1} of calorific value. On the completion and testing, it was observed that the incinerator has a fast heat ingrate. The maximum capacity of paper to be incinerated was 2 kg and it burnt for 17 – 18 mins, while plastic has 1 kg and burnt for 20 – 30 mins, and combination of plastic and paper was 1.5 kg and burnt for 17 – 35 mins. It indicates that it will takes 2 – 4 hrs to burn a typical household waste. Plastic scraps have high energy values because of its chemical composition. The energy content of a kilogram of plastic (46.3 MJ/kJ) is more than that of some type of coal (32.8 MJ/kJ). Future work could therefore be brought up to develop emission control in the incinerator design for municipal solid waste. This is in response to the large volume of gaseous emissions released into the atmosphere during incineration which may pose environment health risk.

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