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Development of an Incinerator for Performance Evaluation of Municipal Solid Waste as an Alternative Energy Source

Paul A. Ondachi
Department of Mechanical Engineering, Baze University, Abuja, Nigeria
paul.ondachi@bazeuniversity.edu.ng

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ORIGINAL RESEARCH

Abstract — The challenge of municipal solid waste (MSW) management in cities of developing countries, including Abuja, poses a serious threat to environmental sustainability. An effective and economic approach to solving this problem is converting the organic fraction of the collected waste to energy by direct incineration. This requires knowledge of technical parameters of the MSW. Design, construction and performance analysis of an incinerator for treatment of organic waste was carried out in this work applying a methodology of standard mechanical engineering design principles. The aim of this study is to develop an incinerator that can be employed to treat organic fraction of municipal solid wastes (MSW) for the purpose of energy recovery, using Abuja's MSW as a test case. Required combustion parameters of the MSW were thereby obtained. The fixed grate experimental-scale incinerator developed in this work has dimensions of 1000 mm x 800 mm x 800 mm (L x H x W) and a waste treating capacity of 30 kg/hr..Performance tests conducted on the incinerator showed that burn-out time of 30 minutes was achieved in the incineration of organic waste for a test batch size of 6 kg and the average incinerator hearth temperature attained was 618℃.The carbon monoxide emission was found to be116.97 g per ton of MSW which is very much lower than internationally allowed value of 125g/ton of MSW. The incinerator's potential for steam generation for electric power production was determined to be 64.86 kg/sec at 8 bar and 460 ℃, pressure and temperature, respectively.

Keywords— Alternative energy source, Incinerator, Municipal solid waste, Organic waste, Performance analysis

1 Introduction

1.1 WASTE GENERATION AND MANAGEMENT

Waste generation is as a result of human existence and activities on earth. These activities give rise to residues and by-products which will require proper disposal for the purpose of public health and environmental sustainability. The management of municipal solid waste is subdivided into four components, viz: reduction, composting, waste to energy and disposal (World Bank, 2018). Globally, waste generation is reported to be on the increase (Rogoff, 2019). Table 1 gives a global perspective of waste generation and management where it is seen that consistent with the known factor of socio- . economic power, the more advanced countries have higher MSW generation rate per capita than in the poorer developing regions of the world A readiness to handle such an exponential increase in waste generation must be rapidly developed globally, especially in sub-Sahara Africa where existing waste disposal capacity is reported to be very low. Waste incineration has a proven capacity to reduce waste volume by about 80% (Ghosh et al, 2020) and is therefore well suited as a strategy for MSW management, especially when combined with energy recovery.

The challenge of municipal solid waste (MSW) management in cities of developing countries, including Abuja, poses a serious threat to environmental sustainability. An effective and economic approach to solving this problem is converting the organic fraction of the collected waste to energy by direct incineration. This requires knowledge of technical parameters of the MSW.

*Corresponding Author

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Table 1: Projected Estimates of MSW Generation Rates Worldwide (Rogoff, 2019)

Region	Total Urban Population (Millions)	Urban MSW Generation per capita (kg/day)
Africa	518	0.85
East Asia and Pacific	1,230	1.52
Western and Central Asia	240	1.48
Latin America and the Caribbean	466	1.56
Middle East and North Africa	257	1.43
OECD	842	2.07
South Asia	734	0.77
Total	4,287	1.42 (Average)

Waste-to-energy conversion as a strategy in MSW management can be achieved through direct incineration for energy recovery, biogas production through fermentation of biomass component of the MSW, pyrolysis and gasification of the waste, among many other conversion technologies available. The waste-to-energy approach through incineration requires the installation of purpose-built incinerators.

The energy crisis in countries like Nigeria makes this strategy of converting waste to energy to be a very viable approach since it provides the concept of 'killing two birds with one stone' by helping to provide a framework for solving the energy poverty while simultaneously addressing the issue of poor waste management.

1.2 WASTE INCINERATION

Incineration of waste is a controlled combustion process used as a thermal treatment technique with the primary objective of volume reduction and energy recovery from the wastes. Heat produced from combustion process of the WtE scheme is recovered and converted to electric power or used directly for space heating and other processes(Moharir et al, 2019). During incineration, the organic matter of the waste is burnt and heat energy is released, while the inert inorganic content goes out in the form of ash. Therefore, the end products of incineration include ash, heat, and combustion gases. Fig. 1 shows the overall flow chart of the incineration process.

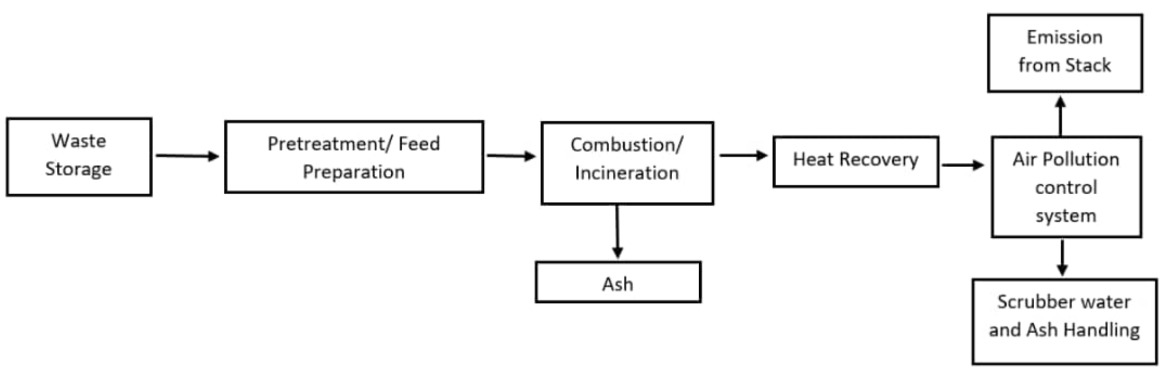

Fig. 1: General flow chart of the incineration process (adapted from Moharir et al, 2019)

For optimal incineration efficiency, focus should be on the time taken, temperature of the process, and turbulence within the process known as 3 T's (Moharir et al, 2019). These three parameters play very important roles in determining the efficiency of an incineration process. Time in any incinerator system corresponds to the residence time of flue gases in the secondary combustion system, while temperature in

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the incineration chamber(s) is responsible for complete combustion of the wastes. Incineration temperatures may be as high as1600°C(Yan et al, 2021).Turbulence represents the agitation experienced by the MSW together with the combustion air in the chambers. Sufficient turbulence is a necessary parameter for high combustion efficiency.

INCINERATION CHAMBERS

For most furnaces, combustion takes place in the primary and secondary combustion chambers. However, some incinerators, especially those designed to handle sorted organic waste, have only one combustion chamber.The primary combustion chamber is the compartment provided in the incinerator for thermal degradation of the solid waste, while the secondary combustion chamber is intended for complete combustion of any unburnt matter in the exhaust fumes. A primary burner is installed in the primary combustion chamber, which receives hydrocarbon fuel for the purpose of initial ignition.

Most incinerators designed for treatment of hazardous wastes have a secondary combustion chamber incorporated. The primary purpose of a secondary combustion chamber in an incinerator is to ensure complete combustion of all combustible material already converted to gas in the primary chamber. This helps to prevent the release of harmful gases generated by the incinerator from entering the atmosphere. To achieve this, the incineration temperature is raised very high in the presence of additional oxygen, as will destroy such gaseous chemicals by oxidation. The walls of the chamber are thermally lagged for proper insulation. This can be achieved by using materials with refractory properties cladded externally with low conductivity materials.

2 CURRENT DEVELOPMENTS IN WASTE-TO-ENERGY

Waste-to-energy (WtE) refers to the process of generating energy in the form of either electricity or heat. This is either through direct incineration of waste with energy recovery or converting the waste into a fuel source and remains the mostcommon WtE process globally(El Sheltawy et al, 2019).Examples of combustible fuel commodities obtained from MSW processing include methane, methanol, ethanol which may be usedfor energy generation applications. Wastes that have no recyclable value are ideally suited for conversion to energy and the process represents a veritable means of MSW management. Generating energy from waste is classified as a renewable source (El Sheltawy et al, 2019). Obtaining energy from waste leads to directly proportional reduction in energy generation using fossil sources which are non-renewable and release carbon dioxide and other greenhouse gases to the atmosphere. Energy from waste is from the organic fraction of MSW which is mainly biomass from plants and other organic sources which can regrow in a relatively short time. The initial capital cost of a typical waste-to-energy plant is approximately 10% of that of solar energy and 66% that of wind energy (World Bank, 2018). The average overall efficiencies of WtE plants are in the range of 22–30% for plants producing only electricity while combined heat and power plant (CHP) has efficiency ranging from30–60% Varley, J., (2022).

3. METHODOLOGY

Standard mechanical engineering design principles were applied for the design of the test incinerator as described below.

3.1. INCINERATOR DESIGN

Determination of incinerator parameters is presented below.

3.1.1 DESIGN ASSUMPTIONS:

i. Type of incinerator: Single (primary) chamber incinerator

ii. MSW batch quantity for incineration: 6 kg

iii. Height of combustion chamber, H = 0.80m

iv. Width of combustion chamber, W = 0.80m.

v. Assumed time to completely burn 6 kg of MSW: 12 minutes

vi. Combustion process in the incinerator is adiabatic. Therefore, incinerator external wall temperature will be equal to ambient temperature (i.e., 32^{o}C for Abuja (Orisakwe et al, 2017).

vii. Assumed incineration temperature: 800^{o}C (MSW incineration temperature varies from 500 – 1600^{o}C, Yan et al, 2021).

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3.1.2 DETERMINATION OF INCINERATOR PARAMETERS

Calculation of MSW incineration batch volume:

With Abuja's MSW density reported as 280 m^3/kg (Ondachi, 2024), waste volume per batchto be handled by the incinerator is obtained as:

$$V = \frac{m}{\rho_{MSW}} \tag{1}$$

where m is the mass of MSW batch to be burnt and is the density of MSW sample.

Calculation of burn rate:

With batch size of6 kg and burn-out time selected as 12 minutes, burn rate is calculated using Equation (2):

$$BR = \frac{m}{t} \tag{2}$$

Where BR is the burn rate; m is the mass of MSW batch size; t is burn-out time.

Calculation of incinerator wall thickness:
Thermal conductivity of Nigerian burnt brick,
k = 0.12 W/m. K (Obidiegwu et al, (2020).
Assuming that conduction is the principal mode of heat transfer through the insulating wall, then the wall thickness, ΔX,is calculated from the conduction heat transfer equation, Equation 3 (Anguruwa & Oluwadare, 2019):

$$Q = \frac{kA\Delta T}{\Delta X} \tag{3}$$

The heat transfer rate is first obtained from the energy yield of the MSW fraction as given by Equation (4):

$$Q = \frac{E_{Actual}}{Burn-out\ time} \tag{4}$$

Energy yield per kg (Lower Calorific Value) from Abuja's MSW's organic fraction, LHV = 19.84 MJ/kg (Ondachi, 2024).

Assuming 80% chemical conversion efficiency (Nandhini et al, 2022), actual energy released, with combustion period of 12 minutes for batch size, may be calculated using Equation 5 (Capareda, S. (2023):

$$E_{Actual} = \eta_{chem} \times LHV \times Batch\ quantity \tag{5}$$

Cross-sectional area for heat transfer across incinerator wall thickness may be obtained as:

$$Area,\ A = Height \times Length = 0.8 \times 1.0 = 0.8\ m^2$$

and with the assumed incineration temperature of 800 °C,

$$\Delta T = 800 - 32 = 768\ ^oC;\ k = 0.1\,W/m.K$$

Therefore, the incinerator wall thickness may be obtained using Equation (6):

$$\Delta X = \frac{k\ A\,\Delta\,T}{Q} \tag{6}$$

Design of fixed grate air distributor:

The air distribution grate is used in this work. It supports the materials to be incinerated and homogeneously distributes the fluidizing air into the bed of solids. This type of grate forms a bubbling fluidized bed (BFB) with in the furnace of the incinerator.

Number and pitch of air distributor orifices:

The number of apertures, N_p, must conform to a geometrical pattern with a fixed pitch, P_n, with a relationship given in Equation (7) (Kafle et al, 2016),for a square pitch as:

$$N_p = \frac{1}{P_n^{\,2}} \tag{7}$$

Surface area of distributor has already been determined to be A = 0.8m^2.

Total area of apertures may be estimated using Equation 8 (Kafle et al, 2016).

$$\sum A_{Aperture} = kA_{Distr} \tag{8}$$

where k is a factor to allow for rigidity of the air distributor plate. A factor of 0.3 is used in this work.

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Velocity of combustion air across the air distributor:

Using an air-fuel ratio of 5.89: 1for the MSW incineration, the quantity of actual air,m_{Actual}, for a batch size of 6 kgwas obtained as35.34 kg.

The assumed burn-out time of 12 minutes gives the actual air mass flow rate, m^*_{Actual} using Equation (9).

$$m^*_{Actual} = \frac{m_{Actual}}{Burn-out\,time} \tag{9}$$

Combustion air volumetric flow rate is obtained from Equation (10).

$$Q_A = \frac{m^*_{Actual}}{\rho} \tag{10}$$

where ρ is the density of the combustion air;

With the air distributor total aperture area, $\sum A_{Aperture}$ known, the combustion air speed, U, across the distributor is calculated by applying Equation 8 as $U = \frac{Q_A}{\sum A_{Aperture}}$

Design of chimney:

The capacity of a chimney required to handle the flue gases depends on the potential the pressure difference created by the temperature difference between the inside and outside air (also known as chimney draft), chimney height and its cross-sectional area (Pheapradit, (2024).

i. Chimney height:
Chimney height should be adequate to minimise air pollution in the immediate environment of the test. The chimney draft pulls the flue gas from the combustion chamber through the chimney and out of the incinerator. The chimney draft, $\Delta \boldsymbol{p}$, is
stated as in Equation 11, (Pheapradit, (2024):

$$\Delta p = h\,(\rho_o - \rho_i)g \tag{11}$$

Where h = height of chimney (m) ρ_o = density of air the outside incinerator,ρ_i = density of flue gas; g = 9.81 is the acceleration due to gravity.
Noting that air is the main constituent of the flue gas, Equation (11) can alternatively be expressed as in Equation (12) (Pheapradit, (2024):

$$\Delta p = 0.0465 h\,\Delta T \tag{12}$$

Where ΔT = air temperature difference between the inside and outside of the incinerator.

$$(\Delta T = 800 - 32 = 768\,^oC)$$

Hence, the chimney height is determined from Equation (13).

$$h = \frac{\Delta p}{0.0465\Delta T} \tag{13}$$

The chimney draft Δp, may be obtained from the chimney draft chart as 100 Pa (Pheapradit, (2024).
ii. Chimney cross-sectional area
The chimney cross-sectional area required may be calculated using the continuity equation as

$$A = \frac{\phi_{Air}}{v} \tag{14}$$

Where A = cross-sectional area of chimney; ϕ_{Air} = volumetric flow rate of flue gases at chimney temperature and pressure and v = velocity of flow through the chimney.

Using the thermodynamic equation of state, $\frac{PV}{T} = C$, the volumetric flow rate of flue gases through the chimney is obtained as:

$$\phi_2 = \frac{T_2 P_1 \phi_1}{T_1 P_2} \tag{15}$$

$\phi_1 = 041\; m^3/sec$ (air flow rate into the incinerator;T_1 and T_2 are temperature outside and inside the incinerator, respectively. P_1 and P_2 are pressures within and without the incinerator respectively. T_1 = 32 ^{o}C; T_2 = 800 ^{o}C; P_1 = 101.3 kPa; $P_2 = P_1 + \Delta P$ = 101.3 + 0.1 = 101.4 kPa.
Hence, ϕ_2 = 0.144 m^3/sec.
A flow speed of 9.5 m/s through the chimney is selected (Pheapradit, (2024).
Therefore, from the continuity equation, cross-sectional area of chimney was obtained as:

$$A = \frac{\phi_{Air}}{v}$$

Using a circular duct, the chimney diameter is obtained using Equation (16) as:

$$d = \sqrt{\frac{4A}{\pi}} \tag{16}$$

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Design of ash box

This serves as a collector for the ash resulting from the incineration process. The ash box makes collecting the ash easy for final disposal. It should be installed under the grate and flush with the internal walls such that it is able to collect all the ashes falling from the incineration process above it.

i. Ash box material: Material selected for constructing the ash box must be fire resistant in order to withstand the heat of the incineration process without any effect. Cast iron is selected as material for the ash box of this test incinerator.

ii. Ash box dimensions

The design for the ash box will be for weekly disposal. The incinerator is designed for an MSW batch size of 6 kg. Within a working period of 10 hours in a day, it is feasible to burn 10 batches. Therefore, for 6 days in a week,

$Mass\,of\;MSW = 10 \times 6 \times 6 \quad = \quad 360\,kg$ of MSW can be burnt in the incinerator.

The ash formed per week will be given by Equation (17) as:

$$m_{Ash} = y_{Ash}\; m_{Ash} \tag{17}$$

Where y_{Ash} is the per cent ash content in the MSW (obtained from proximate analysis of the MSW sample, 3.86%; (Ondachi, 2024) and m_{MSW} is the mass of MSW burnt within the period.

Volume of ash formed per week is calculated using Equation (18),

$$V = \frac{Mass\,of\;ash}{Density\,of\;ash} \tag{18}$$

Typical bottom ash density from Nigerian MSW incineration is reported to be 1,675 kg/m^3 (Abdullahi, 2009).

With a plan area of 0.8 m^2, the minimum depth of the ash box will be obtained using Equation (19)

$$d = \frac{V}{A} \tag{19}$$

3.2. PERFORMANCE EVALUATION

Effectiveness and environmental safety of the incineration of Abuja's MSW within an incinerator were evaluated using parameters such as flue gas analysis, incinerator hearth temperature achieved and the impact of the incineration on the immediate environment. To carry out the performance evaluation samples organic waste from Lugbe, Galadimawa and Dutse-Alhaji districts of Abuja were completely burnt in the developed incinerator in batch sizes.

For the flue gas analysis, the probe for the special purpose gas analyser was connected to flue stack of the incinerator. Readings of values for carbon monoxide, nitrogen oxides (NO_x), sulphur dioxide (SO_2) and carbon dioxide were taken after combustion process had started and stabilised. Results obtained in this study are reported in Table 3.

The incinerator temperature achieved will be recorded by installing a thermocouple system on the incinerator. The sensor of the thermocouple was inserted in the free board region of the incinerator where the after-burning process takes place. During the incineration of each sample, temperatures were recorded until the maximum value is reached. Results are as shown in Table 4.

A special purpose air quality monitor was used to monitor the presence of components of flue gases such as carbon dioxide, unburnt hydrocarbon, carbon monoxide, etc., in the immediate atmosphere during the burning of the MSW samples within the incinerator so as to compare with values before the incineration and also with values allowed by regulators. This will help to validate the concept that closed –space incineration of Abuja's MSW will not be hazardous to the environment. Results are as shown in Table 5.

The set up for the incinerator performance tests is as shown in Fig. 2.

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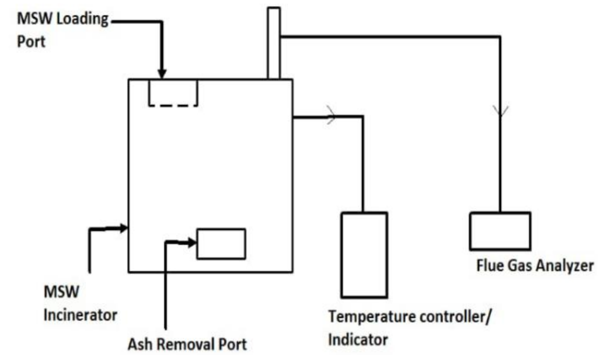

Fig. 2: Schematic diagram showing set up for incinerator performance tests

4. RESULTS AND DISCUSSION

4.1. RESULTS

The results obtained for incinerator dimensions and other parameters are presented in Tables 2.

Table 2: Summary of incinerator design values

S/N	Parameter	Value
1	Batch size	6 kg
2	Incinerator dimensions	1.0 m x 0.8 m x 0.8 m
3	Incinerator wall thickness	0.065 m
4	Combustion chamber volume	0.64 m^3
5	Batch burn-out time	12 min.
6	Burn rate	30 kg/hr
7	Air mass flow rate	0.049 kg/sec.
8	No. of air distributor apertures	620
9.	Distributor aperture dimensions	13.5 mm x 28 mm
10.	Air distributor pitch	40 mm
11.	Chimney height	3.0 m
12.	Chimney diameter	14 cm
13.	Ash box capacity	15 litres
14.	Ash box material	Cast iron

Results for flue gas analysis of incineration of Abuja's MSW are presented in Table 3.

Table 3: Abuja's MSW Incineration Flue Gas Analysis

Component	MSW Sample				Amount of component in Flue gas (g/ton of MSW)	UK Regulation (g/ton MSW) (Trozzi, 2013)
	Dutse-Alhaji	Galadimawa	Lugbe	Aggregate		
CO (%)	0.01	0.08	0.16	0.083	116.97	125
CO_2 (%)	0.23	0.02	--	0.16	225.48	--

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O_2 (%)	-	-	-		--	--
Hydrocarbons (ppm)	106.3	200	122.4	142.9	20.14	--
NO_X (%)	-	-	-		--	2500

Maximum incinerator hearth temperatures obtained for the various MSW samples are shown in Table 4.

Table 4: Maximum Incinerator Hearth Temperature for Abuja' MSW Samples

Item	Lugbe Sample	Galadimawa Sample	Dutse-Alhaji Sample	Average
Max. Hearth Temp. (°C)	741	476	637	618
Batch Quantity (kg)	6	5.5	5	5.5
Batch Burn-out Time (min)	27.5	39	33	33.2
Burn Rate (Tons/hr)	13	8.5	9.1	10.2

The impacts of incineration of the MSW samples on environmental air quality are reflected in Table 5.

Table 5: Impact of Incineration of Abuja's MSW on Environmental Air Quality

	MSW Samples					
	Dutse- Alhaji		Lugbe		Galadimawa	
Component	Initial reading	Reading during test	Initial reading	Reading during test	Initial reading	Reading during test
O_2 (%)	1.5	1.5	1.5	1.93	2.9	3.1
CO_2 (%)	-	-	-	-	-	-
CO (ppm)	5.0	3.0	11.0	2.3	23.3	6.3
Rel. Humidity (%)	57.7	50.6	62.4	50.4	31.8	30.3
ambient Temp. (°C)	32.3	34.8	30.7	34.8	43.4	43.3

Fig. 3 shows the views of the incinerator in 3rd angle projection while the incinerator as built is shown in Fig.4.

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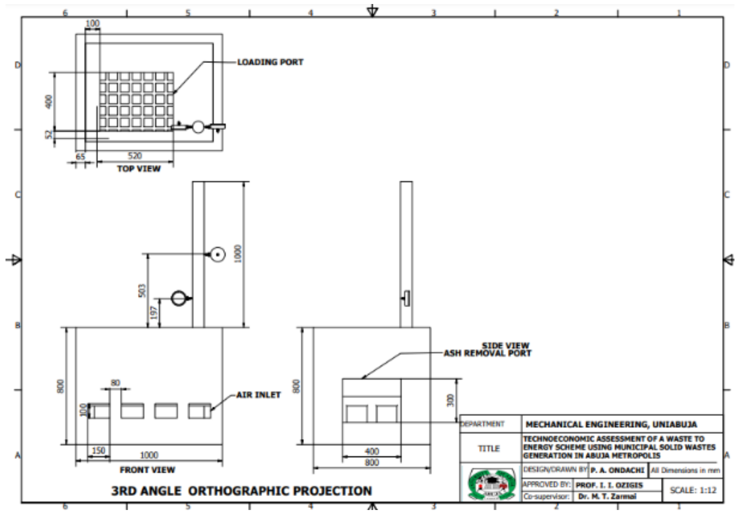

Fig. 3: Orthographic views of Experimental Scale Incinerator for Abuja's MSW

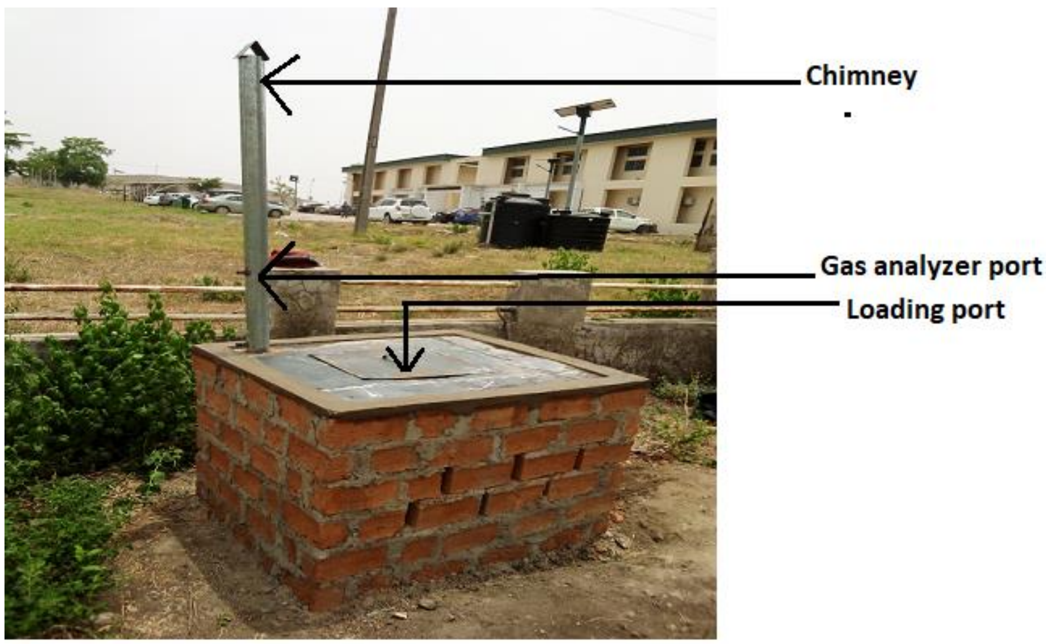

Fig. 4: Test Incinerator, as built [Author's photograph]

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4.2. DISCUSSION

4.2.1 INCINERATOR DEVELOPMENT

The geometric dimensions determined for the incinerator proved adequate for the purpose of air movement within the combustion chamber which is important for creation of turbulence and heat release since the size of combustion chamber affects the oxygen concentration for the combustion process (Peng et al, 2023).

The average incineration temperature of up to 745 ℃ achieved in the tests (Table 4) compares well with results of other researchers since the combustion temperature must be regulated to avoid corrosion issues with the grate materials and other metallic structures of the incinerator and adequate to destroy the gaseous pollutants (Magnanelli et al, 2020; US EPA, 1999).

The developed incinerator showed capacity to produce superheated steam for power generation at a rate of 64.86 kg/sec at 8 bar and 460°C, pressure and temperature, respectively. This steam flow rate has been shown from analysis to be able to sustain 2 X 27. 45 MW steam turbine (Ondachi, 2024).

4.2.2 INCINERATOR PERFORMANCE EVALUATION

The performance evaluation carried revealed that carbon monoxide emission from the incinerator (Table 3) was shown to be below internationally allowed limits of 125 g/ton of MSW burnt (Trozzi, 2009), which is an indication of good performance since it will have minimal negative impact on the environment. Weekly ash formation from operating the incinerator was calculated to be 23.16 kg for the 50kg/hr incinerator which can be easily transferred to final disposal site.

Values of incineration temperatures in this study also compare well with values published in literature. As may be observed from Table 4, the highest incineration temperature of 741 ℃ was obtained for Lugbe sample while Galadimawa and Dutse-Alhaji samples had maximum temperatures of 476 and 637 ℃, respectively. Similar works by Tayachew Nega et al achieved 800 ℃ while Anca-Couce et al obtained a value of 1079 ℃ with wood incineration (Anca-Couce, 2021).

With the limitation of superheater metal temperature to about 440 ℃ in order to avoid corrosion effects (Karomah, 2022), the thermal performance of each sample of Abuja's MSW when incinerated appears to be excellent. Also, from Table 4, burn-out time (incineration process time) was 27.5, 39, and 33 minutes for Lugbe, Galadimawa and Dutse-Alhaji samples. Yang et al (2002) obtained a process time of 60 minutes in a similar study. For the Abuja MSW samples burn-out time per kg MSW were 4.58, 7.09 and 6.6 minutes for Lugbe, Galadimawa and Dutse-Alhaji samples, respectively. This again shows better incineration performance for Lugbe sample.

The incinerator demonstrated a potential for steam generation for electric power production from Abuja's MSW calculated to be 32. 43 kg/sec in two streams which is capable to drive a 55 MW steam turbine plant with the rated boiler and condenser pressures of 8 MPa and 5.6 kPa, respectively, at a turbine isentropic efficiency of 80% in two streams of 27.45 MW.

From Table 5, it may be seen that enclosed incineration of Abuja's MSW has minimal negative impact on the environment.

5. CONCLUSION

The development of an incinerator to treat Abuja's municipal solid wastes for electricity has been carried out in this work. Considering the results obtained from the research work, the following conclusions are hereby outlined:

1 Locally available burnt bricks were found suitable as refractory and insulation material for incinerator construction.

2. The test incinerator designed and constructed for this work has a waste treating capacity of 50kg/hour showed good performance with carbon monoxide emission remaining below internationally allowed value of 125g/ton of MSW.

3. Performance evaluation of the incineration process of Abuja's MSW revealed maximum incineration temperature of 618°C which is very suitable for production of superheated steam for generation of electric power.

4. The developed incinerator's potential for steam generation for electric power production was determined to be 64.86 kg/sec at 8 bar and 460 ℃, pressure and temperature, respectively, which is of key economic significance.

A limitation encountered in this study is the use of an automobile exhaust gas analyzer in place of a general purpose flue gas analyzer.

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