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Development and Performance Evaluation of a Small Scale Municipal Solid Waste Incineration Plant

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Abstract This study presents the design and testing of a waste-to-energy plant by incineration of small scale municipal solid waste to produce steam for electricity production. The average total waste generated within the study area was found to be 55,800kg/day, with an estimated calorific value of 13,958kJ/kg. The waste samples were collected, dried, shredded and weighed in order to reduce the moisture content to the acceptable minimum and decreases the surface area of the sample that will allow easier penetration of heat. The incinerator was designed using CATIA-5 software. The key performance indices of the developed plant are maximum furnace temperature, residence time, mass flow rate, steam pressures and amount of steam generated keeping the mass of waste constant per test but varying the air flow. The moving grate is inclined at an angle of 12° while the volume of the incineration combustion chamber was calculated to be $0.267m^3$. 150kg of small scale waste was fed into the combustion chamber of the incinerator to produce heat in order to fire the boiler filled to 70 litre capacity level. Tests were carried out with natural air flow and forced air supplied through the primary air nozzles at an air velocity of 6.2m/s. The obtained temperature/pressure results were: 464°C/5 bar and 528°C/7 bar and 542°C/7 bar for tests 1, 2 and 3 respectively. The steam produced in the boiler was able to run a steam turbine used to generate electricity. Preliminary results showed that such a plant could be used to complement the power supplied to the University as a set of 36 - 12V DC bulbs were powered for 15 minutes.

Keywords: *municipal solid waste, incineration, electricity production, small scale waste, energy*

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1. Introduction

Municipal solid waste (MSW) is generated from household, commercial, and institutional activities. MSW refers to a common waste such as food scraps, paper, plastics, clothing, glass, metals, wood, street sweepings, landscape and tree trimmings and general wastes from recreational areas. It does not include industrial, hazardous, and construction wastes [1,2,3].

MSW is constantly increasing as a result of rapid economic growth, the continued improvement of living standard, population growth, urbanization [4] and mass production and consumption of goods [5]. This causes environmental pollution, health hazards, takes up limited land resources, pollute water and air, and consequently lead to serious environmental trouble. Proper waste treatment is therefore an urgent and important task for the continued development of cities [6].

Small scale wastes comprise of household waste, wood waste, plastic, paper or agricultural waste, and some components of industrial and medical waste, which are non hazardous and less complex to handle [7].

Incineration is a thermal process wherein the combustible components of a solid waste stream are thermally oxidized to produce heat energy that can be used to create steam for use in generating electrical power, for industrial processes, or for district heating. In addition to thermal energy, products of the incineration process include bottom ash, fly ash, and flue gas [8]. The standard approach for the recovery of energy from the incineration of MSW is to utilise the combustion heat through a boiler to generate steam which can be used for the generation of power via a steam turbine and/or used for heating. Waste management in Nigeria is an issue of major concern, with landfills being overstretched and also emit carbon dioxide (CO_2) as well as methane (CH_4) to the atmosphere. Open dumpsites usage has a negative impact on the atmosphere, groundwater and health effects on human beings. In place where available, the landfills are not well designed as leachate flows freely.

Coverting these large quantities of waste into usable energy, using the appropriate technology, will go a long way in improving the economy of the country through increased energy supply and reduction in CO_2 and CH_4 emissions from landfills [9]. Nigeria has huge energy potential both renewable and non-renewable which constitutes a good platform for the development of an effective energy plan.

Indiscriminate dumping of solid waste and poor collection system in a populated community over a long period of time (i.e. two or three weeks) cause many problems. Odors, flies, rats, roaches, crickets, wandering dogs and cats, and fires would dispel any remaining doubts of the importance of proper solid waste management.

MSW have been receiving attention for various reasons over time across the world [10-21]. Maiduguri, the state capital of Borno state, in northern Nigeria located on latitude 11.85° north and longitude 13.08° east has been the epicentre of the Boko Haram insurgency from 2009 to date; with various impacts such as loss of lives, destruction of properties as well as vandalization of electrical installations all over the state. This research aims at developing a small scale waste incineration plant for electricity generation in the University of Maiduguri, while the objectives are to: estimate the amount and composition of MSW generated within the University of Maiduguri (Academic, commercial, hostel and residential areas), design and construct a Waste-to-Energy (WTE) incineration plant that could process 150kg of small scale waste (i.e. paper, polythene bags, garden trimmings, hay, straw, leaves, etc...) per hour; use the constructed incinerator to generate electricity and finally evaluate the performance of the developed WTE plant.

2. Materials and Methods

2.1. Instruments/equipment

The materials used for the experiments are: fire bricks, angle iron, while the equipment used for these tests were: one (1) digital tachometer DT-2234 B photo type, 0.1 rpm-5-999 rpm, 1 rpm-1,000-99,999 rpm; one (1) Digital Anemometer CT LUTRON SP-8001, one (1) digital stop watch SUNWAY S1-1025, two (2) RKC Rex - C700 digital thermocouples with ranges of 0-1400°C, a digital METLER TOLEDO weighing machine and CATIA- 5 software was used for the calculations and design in this research.

2.2. Experimental Procedure

Experiments were performed on the plant to determine its effectiveness in terms of steam generation, pressure build-up and MSW combustion. 150kg of small scale MSW (i.e. in each test) was used for each test and loaded via the hopper. It is then conveyed into the combustion chamber of the incinerator on the grate with the help of the electric motor and gear system. The boiler water used throughout the experiments was sourced from the tap water, supplied by the nearby water resources authority, in order to minimize risks of corrosion and as well ensure freedom from other sediments. A hose was used to connect the tap water to the feed pipe of the boiler which has capacity to accommodate 125 liters of water. The water quantity used throughout was maintained at 70 liters to provide sufficient space for the steam generation. Pressure measurements were carried out using two (2) 25 bar pressure gauges mounted on the boiler to determine the pressure developed in the boiler and secondly to determine and control the pressure at the turbine entrance. Temperature measurements (i.e. the temperature of the boiling water and temperature within the combustion chamber) were done using digital thermocouples with wire probes while mercury in glass thermometer was used to determine the ambient temperature as well as the initial temperature of the water. Heat released by the burning MSW was used to fire the boiler and the steam produced was piped to a turbine generator in order to generate electricity. The ash was collected at the discharge point. The flue gases are released through the chimney (draft).

The test was then repeated while varying the number of air supply nozzles as zero (0), three (3) and five (5) nozzles at an air speed of 6.2m/s.

3. Theoretical Design Analysis

3.1. Incinerator Sizing

The internal volume requirement excludes the ash pit and can be evaluated from [22]:

$$Vi_{\min} = \frac{Q_{thr}}{258,750W/m^3} \quad (1)$$

$$Q_{thr} = \frac{M_b}{Q_{av}} \quad (2)$$

where:
Vi_{min} is minimum theoretical internal volume (m^3)
$Q_{thr}$is total heat released (W)
M_b is the mass of refuse burned per hour (kg/h) and
Q_{av} is average heating value (kJ/kg).

The total amount of municipal solid waste (MSW) is mainly affected by the population and the amount of waste produced per capita. The expression of the amount of municipal solid waste production is [23]:

$$Total\ MSW = MSW\ per\ capita \times population \quad (3)$$

Generation rates of MSW per capita were found to vary between 0.68 kg and 1.8 kg per person per day [24].

Therefore the average waste generated was estimated to be 1.23kg/capita/day and the University of Maiduguri houses about 45,000 people; students, staff and business owners.

3.2. Incinerator Furnace Geometry

Most incinerators employ an inclined moving grate where the waste is dried, devolatilized and burned using primary air. To effect complete combustion high velocity secondary air jets are required [25]. Oumarou *et al*, [26] found out that the parallel flow type of incinerator was found to be suitable for the category of low calorific value municipal solid wastes produced in the semiarid regions of northern Nigeria and Niger Republic in West Africa. This is because the burnout of the gaseous species is very well done in parallel flow geometry, where the flue gas is directed through the hottest zone by a distinctive nose. Also, the concept allows pyrolysis gases to pass through the hottest area and therefore are burnt out satisfactorily which is well suited and appropriate for the semi arid regions being considered in this study because of their lower calorific value (LCV).

3.3. Air Ratios

The combustion conditions in the furnace need to be controlled to give near-stoichiometric conditions by splitting up the total combustion air to a primary air and secondary air ratio of 1.3:1.8. The partitioning ratio of primary to secondary air is between 80/20 (old plants) to 40/60 (tendency for new plants). The task of secondary air is to complete the burnout of the hydrocarbons and carbon monoxide. In addition, secondary air can be used as a mixing device for flue gases [27].

The burning of a fuel (e.g., wood, coal, oil, or natural gas) in air is a familiar example of combustion [28].

$$C_6O_{10}H_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O + heat$$

Oxygen starvation often leads to partial combustion of the carbon to CO rather than CO_2: Secondary combustion will take place if the CO and other intermediate products meet with oxygen or non- depleted air at a sufficiently high temperature for gaseous combustion to CO_2 to take place. In an open fire, this secondary combustion can be observed as “flames” immediately above the burning material, as fresh air is drawn into the zone by convection. Since combustion effectiveness is also a function of gas residence time, it is important that the air volume flow is not too great, otherwise the incinerator dimensions would need to be increased with consequent cost penalties [3].

3.4. Residence Time

Residence time is determined by the velocity of the gases and the distance they travel through the combustion chamber [22] as shown:

$$t = \frac{V}{q} \quad (5)$$

Or

$$t = \frac{chamber\ length, m}{gas\ velocity, m/s} \quad (6)$$

Where t is residence time (s), V is combustion chamber volume (m^3), q is combustion gas flow rate, (m^3/s).

3.5. Combustion Analysis of MSW

MSW contains the following elements: *c* kg of carbon (C), *h* kg of hydrogen (H_2), *o* kg of oxygen (O_2), *n* kg of nitrogen (N_2), *s* kg of sulphur (S), *m* kg of moisture, *a* kg of ash [29]:

$$c + h + 0 + n + s + m + a = 1kg\ of\ fuel\ (MSW) \quad (7)$$

The theoretical combustion reaction formulae of the combustible elements of municipal solid waste are expressed by the following equations:

$$C + (O_2 + 3.76N_2) \rightarrow CO_2 + 3.76N_2 \quad (8)$$

$$H + 0.25(O_2 + 3.76N_2) \rightarrow 0.5H_2O + 0.94N_2 \quad (9)$$

$$S + (O_2 + 3.76N_2) \rightarrow SO_2 + 3.76N_2 \quad (10)$$

3.6. Combustion Air Requirement

Table 1. Ultimate analysis of MSW on a percentage by mass [6]

Element	C	H	O	S	N	Moisture	Ash
%	35.5	5.1	23.9	0.5	2.4	15	17.6

Considering theoretical combustion reaction for the elemental analysis of MSW shown in Table 2, the air supply can be obtained using the following reaction;

Carbon (C):

$$\begin{aligned} & C + O_2 \rightarrow CO_2 \\ & 12kgC + 32kgO_2 \rightarrow 44kgCO_2 \end{aligned} \quad (11)$$

Hydrogen (H):

$$\begin{aligned} & H_2 + 0.5O_2 \rightarrow H_2O \\ & 2kgH_2 + 16kgO_2 \rightarrow 18kgH_2O \\ & 1kgH_2 + 8kgO_2 \rightarrow 9kgH_2O \end{aligned} \quad (12)$$

Sulphur (S):

$$\begin{aligned} & S + O_2 \rightarrow SO_2 \\ & 32kgS + 2kgO_2 \rightarrow 64kgSO_2 \\ & 1kgS + 1kgO_2 \rightarrow 2kgSO_2 \end{aligned} \quad (13)$$

Table 2. Oxygen Required per Kilogram of MSW

Constituents	Mass fraction	Oxygen requirement (kg/kg MSW)	Product of combustion (kg/kg MSW)
Carbon (C)	0.355	0.947	1.302
Hydrogen (H)	0.051	0.408	0.459
Sulphur (S)	0.005	0.005	0.01
Oxygen	0.239	-0.239	-
Nitrogen (N)	0.024	-	-
Moisture	0.250	-	-
Ash	0.190	-	-
		1.121	1.771

O_2 required per Kilogram of MSW = 1.121kg

Since oxygen in air is 23% by weight.

3.7. Air Injection

The design of the incinerator has air supply nozzles which freely allow flow of primary air into the combustion chamber. The secondary air was drawn into the combustion chamber by convection which can be observed by flames immediately above the burning waste.

In this research, the injection air nozzles were placed above the grate at the entrance immediately after the loading area.

3.8. Boiler Design

The boiler code provides that the factor of safety shall be at least 5 and the steel of the plates, welded or rivet joint shall have as a minimum of the following ultimate stresses [30].

Tensile stress, σ_{ut} = 385 MN/m^2

Compressive stress, σ_{uc} = 665 MN/m^2

Shear stress, τ = 308 MN/m

3.9. Volume of the Boiler

Volume of the boiler is determined by

$$V = \pi R_i^2 l \tag{14}$$

Where

V is the volume of the boiler

R_i is the radius of the boiler

l is the length of the boiler.

3.10. Internal Design Pressure of a Boiler

The internal design pressure is given by [31].

$$P_d = \frac{\sigma_u \times t}{R_i \times f_s} \tag{15}$$

where, P_d = Internal design pressure on inside of the boiler (N/m^2)

σ_u = Ultimate strength of plate (N/m^2)

t = Thickness of plate (m)

R_i = Internal radius of drum (m)

f_s = Factor of safety (ultimate strength divided by allowable working stress)

3.11. Stresses in Tubes and Drums

Stresses are induced in different parts of an operating boiler by the temperatures and pressures of hot flue gases, feed water and steam respectively. The magnitudes of these stresses must be known so that the boiler will be operated under safe conditions [30].

- Circumferential or hoop stress
- Longitudinal stress

$$\sigma_{t1} = \frac{P_d \times D_i}{2t} \tag{16}$$

where, P_d = Internal design pressure of the drum or shell (N/m^2)

σ_{t1} = Circumferential or hoops stress (N/m^2)

t= Thickness of plate (m)

$$\sigma_{t1} = \frac{5.8 \times 0.4}{2 \times 0.003} = 38.7 MN/m^2$$

$$\sigma_{t2} = \frac{P_d \times D_i}{4t} \tag{17}$$

where, σ_{t2} = Longitudinal stress (N/m^2)

Di = Internal diameter of drum (m).

$$\sigma_{t2} = \frac{5.8 \times 0.4}{4 \times 0.003} = 19.3 MN/m^2$$

3.12. Boiler Efficiency

Boiler efficiency varies with different types of fuels [32].

$$\eta = \frac{m_s\left(h_s - h_{fw}\right)}{LCV} \times 100\% \tag{18}$$

where, η= Efficiency of the boiler

hs = Enthalpy of saturated steam at operating pressure (kJ/kg)

hfw= Enthalpy of feed water (kJ/kg)

ms= Mass of steam formed per hour (kg/h)

4. Results and Discussion

The generation and composition of waste in the study area vary according to changes in academic period and commercial activities, consumption patterns and season of the year as well as days of the week.

The wastes collected were physically sorted after drying, with the following composition as shown in Figure 1.

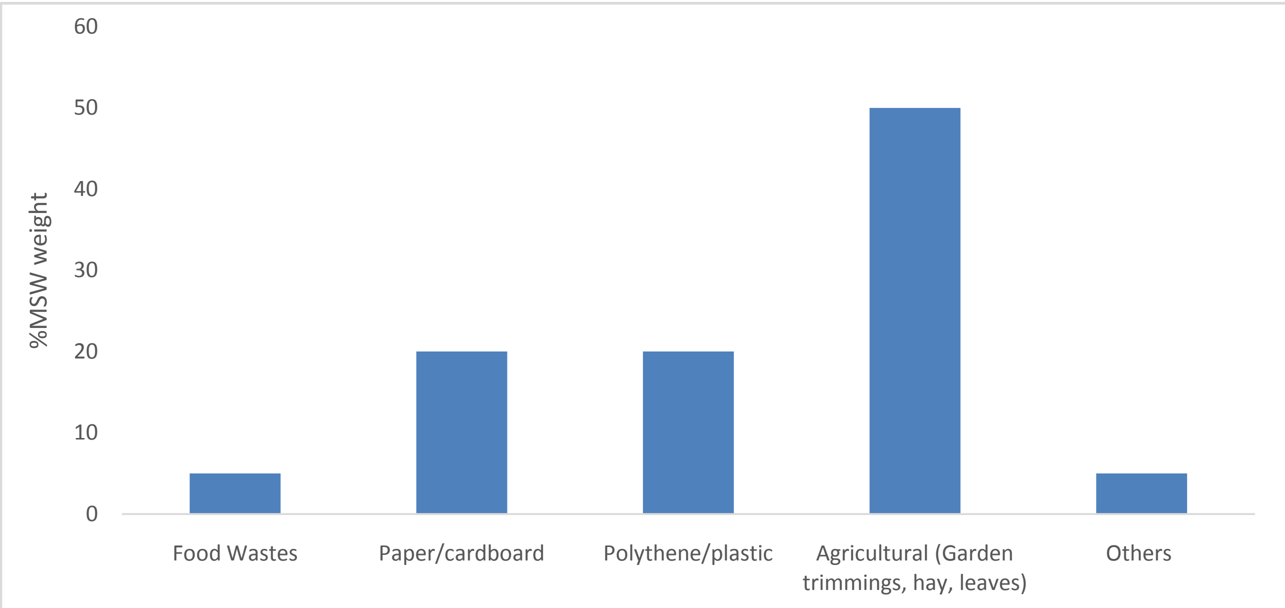

Figure 1. Physical components of the MSW in the Study Area

These types of wastes were selected due to their low pollution effect if properly incinerated. Thus, to ensure the least pollution, critical parameters were considered in the design of the incineration plant as shown in Table 3.

Table 3. Summary of Incinerator Design and Performance Parameters

S/No.	Design Parameter	Value
1.	**Qthr**	9790 kW
2.	Average Waste Produced	55,800 kg/day
3.	Higher Calorific Value (HCV)	15,090 kJ/kg
4.	Lower Calorific Value (LCV)	13,958 kJ/kg
5.	**Design Tool**	CATIA-5 software
6.	Incinerator design capacity	150 kg per hour
7.	Atmospheric temperature	305 K
8.	Combustion chamber temperature	1473 K
9.	Vi_{min}	0.267 m^3
10.	**Incinerator wall**	Fire bricks of 40 x 70 x 120 mm
11.	Boiler volume	0.126 m^3
12	**Draft**	natural draft (draft produced by a chimney alone)
13.	**Frame**	2”x2” angle iron (1.5m x 0.5m x 0.9m).
14.	**Grate Design**	Moving Grate (MG) inclined at 12^0 to the horizontal
	Internal Design Pressure	11.55 *bar*
	Oxygen required for Carbon	0.947kg / kg MSW
	Oxygen required for Hydrogen	0.408 kg/kg MSW
	Oxygen required for Sulphur	0.005 kg/kg MSW
	Air required	4.87 kg/kg MSW
15.	**Cost**	=N= 269,100 ($ 525.00)

4.1. Description of the Powerplant

The plant (Figure 2, Plate 1) consists of the incinerator with walls made of firebricks and plastered on the outside, which houses the combustion chamber, boiler, grate, hopper, exhaust and a discharge; other external parts are the pipes with their pressure gauges for steam discharge and feed water, turbine, alternator, electric motor and gearbox. The MSW is loaded through a hopper before being conveyed onto the grate by the electric motor and gearbox to the combustion chamber. The heat liberated during combustion was used by the boiler to produce steam, which drives a turbine.

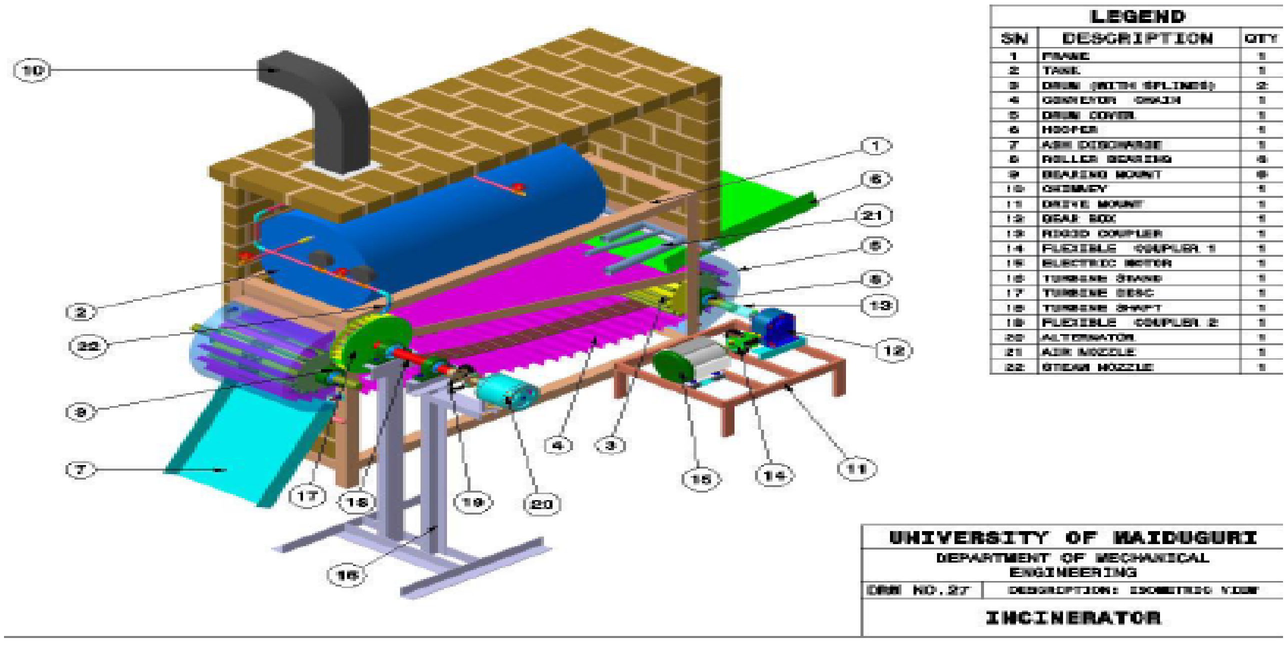

Figure 2. Schematic diagram of the Incinerator Set-up

Plate 1. General view of complete plant set up

The key performance indices of the developed plant are maximum furnace temperature, residence time, mass flow rate, steam pressures and amount of steam generated keeping the mass of waste constant all through and varying the air flow.

Table 4 shows the results obtained from three different tests for variation of primary air nozzles with furnace temperature, residence time, flow rate, pressure and steam produced.

4.2. Rate of Steam Generation

Table 5 shows the steam generation analysis with respect to combustion air flow, in all the tests conducted.

Table 4. Variation of furnace temperature, residence time, flow rate, pressure and steam produced with number of air nozzle.

No of air nozzles	Furnace temperature (^oC)	Residence time (s)	Flow rate (kgs)	Pressure (Bar)	Steam produced (kg)
None	464	30	0.005	5	29
3	528	24	0.00517	6.5	35
5	542	23.6	0.006	7	36

Table 5. Analysis of rate of steam generated

Test	Normal air flow	3 nozzles at 6m/s	5 nozzles at 6m/s
Initial water feed (kg)	70	70	70
MSW weight (kg)	150	150	150
Duration of firing (minutes)	60	53	49
Water Leftover after test (kg)	35	32	30
Pressure (bar)	5	6.5	7
Weight of ash formed (kg)	32.6	30.2	27.6

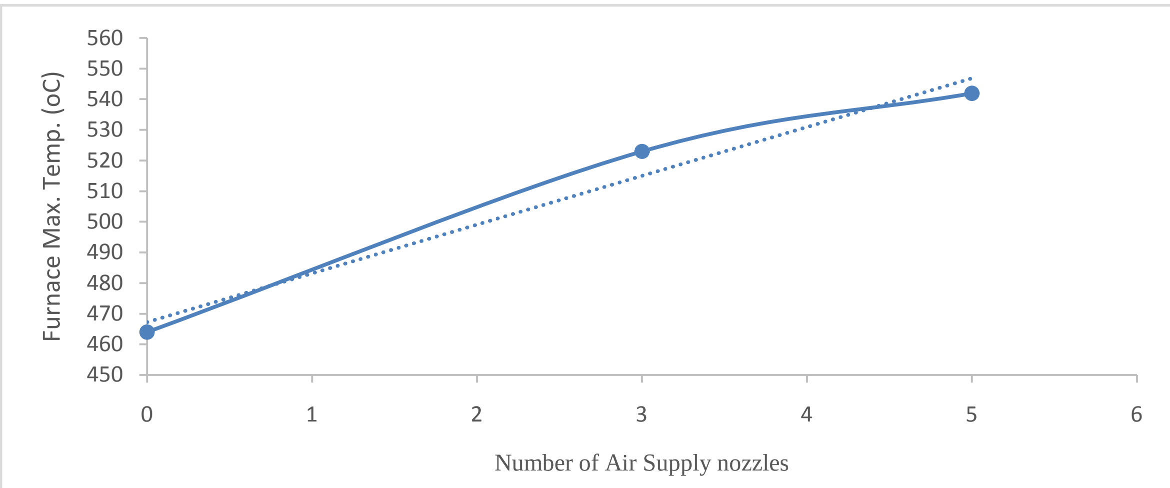

Figure 3. Variation of Air flow with maximum furnace temperature

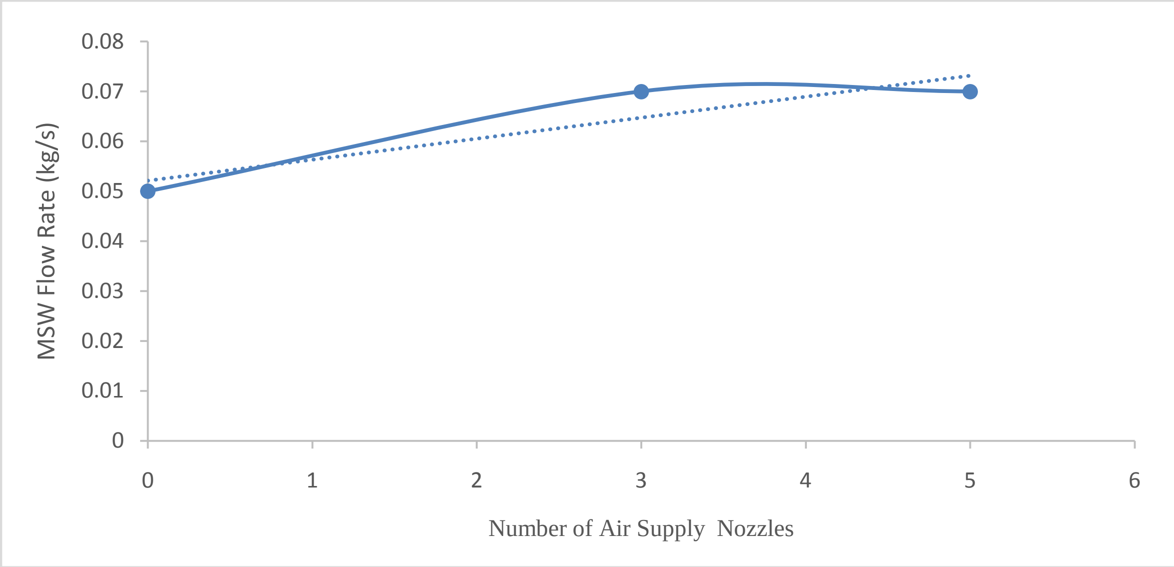

Figure 4. Variation of MSW Flow rate with respect to Air flow

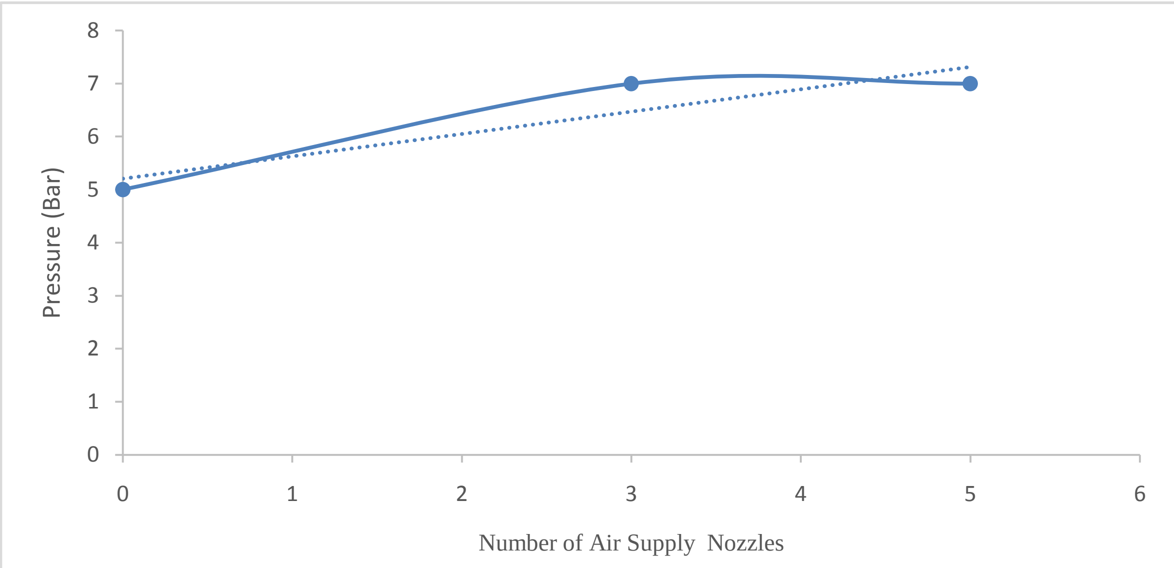

Figure 5. Variation of Air flow with pressure

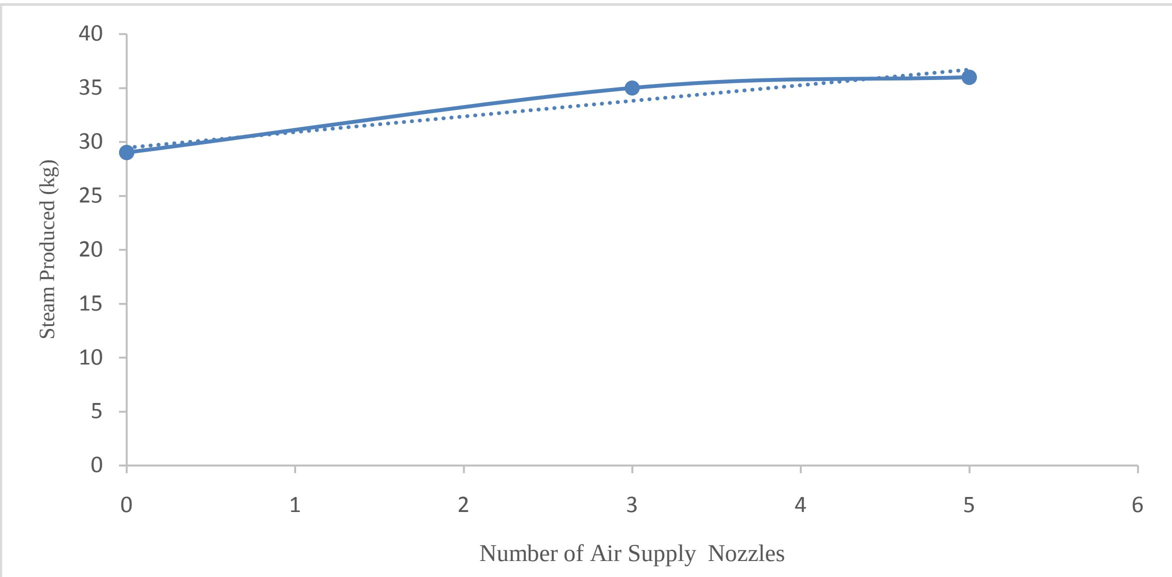

Figure 6. Variation of Air flow with steam produced

The variation of air flow with furnace temperature, MSW flow rate, pressure and steam produced are shown in the Figure 3, Figure 4, Figure 5 and Figure 6.

The quantity of heat energy generated when solid waste is combusted depends directly on the amount of air supply. The lower the air supply the lower the heat available combustion thus resulting in lower temperature in the furnace, hence more air will be needed to raise the temperature and ensure normal combustion.

Test 1 was carried out with ambient air flow which produced a maximum temperature and pressure of 464°C and 5 bar respectively. The flow rate and residence time of the waste were lower in this test due to limited amount of air for combustion. There was a significant amount of smoke as well as traces of unburned MSW in the ash residue.

In test 2 and 3, as more air was supplied through the nozzles with an average speed of 6.2m/s, there was an increase in rate of combustion which was attributed by increase in maximum temperature of 528°C and 542°C respectively, and a pressure of 7bar. There was an increase of MSW flow rate and steam produced, while there was a decrease in residence time within the incineration plant. Pressure drop was the same but there were little or no traces of unburned MSW in the residue ash. These results compare well with those obtained by Olisa, Kotingo, & Amos [33] and Olisa, Amos, & Kotingo [34] where the performance testing of the potential for waste to energy showed that steam was produced at a mass flow rate of 0.2 kg/s with a temperature of 120°C and pressure of 2 bar for a 40 kg load of MSW.

The air nozzles which also serves as the primary air was strategically placed in the combustion chamber in such a way that it was facing the grate at an angle so as to confine the combustion on the grate and to also direct exhaust flue gas towards the draft.

5. Conclusion

The following conclusions were drawn:

i. The amount MSW generated within the University of Maiduguri was estimated at 55,800 kg/day with a per capita generation of 1.2 kg/day/person.
ii. A waste-to-Energy (WTE) incineration plant with a capacity of 150kg/hr of MSW was successfully accomplished based on design specification using CATIA 5. A maximum temperature of 542°C and pressure of 7 bar were recorded.
iii. The steam produced in the boiler was utilized to generate electricity via a steam turbine generator by powering a set of 36- 12V DC bulbs for 15 minutes. This shows that such a plant could be used to complement the power supplied to the University. Such a process of energy recovery from waste will contribute to waste management as a considerable amount of the daily generated solid waste will be converted to energy thereby reducing the volume of solid waste left for disposal.

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