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THERMAL ANALYSIS OF A SMALL SCALE SOLID WASTE-FIRED STEAM BOILER FOR POWER GENERATION IN BENIN CITY, NIGERIA

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ABSTRACT
Thermal analysis of a small scale solid waste-fired steam generator is presented in this paper. The analysis was based on the chosen design specifications which are operating steam pressure and temperature of 20bar and 400°C respectively, solid waste consumption rate of 3.6ton/hr and a furnace utilizing grate-fired technology. The boiler is designed as a possible waste management option in Benin Metropolis and Nigeria at large with energy recovery. The average daily municipal solid waste (MSW) generation in Benin Metropolis was considered in order to assess the availability of the feed stock. A calorific value of 17.49MJ/kg was obtained for the solid waste using Dulong's formula. Calculations based on energy balance in the boiler show that about 7.63kg/s of air is required to combust 1kg/s of MSW to produce about 3.437kg/s of steam. Further calculations show that about 1.4MW of electrical power can be obtained from the produced steam.

Keywords: *Solid waste combustion, Solid waste management, Calorific value, Steam boiler, Waste-to-energy.*

Nomenclature

A_f	cross sectional area of furnace (m^2)
Cp_{fg}	specific heat capacity of flue gas at constant pressure (kJ/kgK)
CV_{sw}	calorific value of solid waste (kJ/kg)
$\dot{m}_{sw}$	solid waste mass flow (kg/s)
$\dot{m}_{air}$	air mass flow (kg/s)
$\dot{m}_s$	steam mass flow rate (kg/s)
P_e	electrical power (kW)
p	condenser pressure (bar)
Q_f	heat released by solid waste (kW)
Q_s	heat absorbed by steam (*kW*)
T	temperature (K)
$\dot{W}_t$	turbine work (kJ/kg)
$\dot{W}_p$	pump work (kJ/kg)
α_e	enthalpy of expanded steam (kJ/kgK)
α_s	enthalpy of steam (kJ/kgK)
α_w	enthalpy of water (kJ/kgK)
η_{ti}	turbine isentropic efficiency (%)
η_p	pump isentropic efficiency (%)
η_{gen}	generator efficiency (%)
η_{tm}	turbine shaft mechanical efficiency (%)
η_b	boiler thermal efficiency (%)

1. INTRODUCTION
Over the years, the development of technologies to utilize renewable energy sources for power generation has become imperative. Despite the advancement achieved on the energy front in the last 20 years, 1.7 billion people are still without access to electricity [1]. With the present impact by greenhouse gas emission, depleting of conventional fuel reserves, increasing demand of energy, rapid population and economic growth rates, health problems from air pollution, etc., the UN General Assembly in 2011 aimed to achieve three clear objectives by 2030. These are ensuring universal access to modern energy service, doubling the global rate of improvement in energy efficiency, and doubling the share of renewable energy in the global energy mix [2].
Since the emergence and need for sustainability, different renewable energy technologies have been investigated and developed for the production of electricity. These renewable energy technologies include: wind, bio-energy, geothermal, solar thermal, hydro, and photovoltaic, etc. [3]. Biomass as bio-energy source has been cited as the world's largest

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renewable energy source and its resources are distributed around the world [4]. Biomass resources are considered renewable because they occur naturally and when properly managed, may be harvested without significant depletion.

Furthermore, in improving the energy efficiency and energy accessibility for sustainable energy for all platforms set by the United Nations, small-scale power technology is seen as an efficient way in achieving this goal. Clean energy from biomass can be realized ranging from small-scale processing plant to an industrial scale. Decentralization of energy distribution via small-scale set ups have several merits which include positive impact on rural development, ease of operation, high economic incentives, reduction of energy loss via transmission, encourages green economy and energy independence, etc. Compared to many other renewable energy options, biomass has the advantage of dispatchability, implying it is controllable and available when needed, similar to fossil fuel electric generation systems [5].

There are several methods to generate energy from biomass and these include thermal, physical, biological and chemical methods. These methods could convert biomass to heat, electricity, liquid fuels (such as bio-oils, ethanol and methanol) and gaseous fuels (such as hydrogen and syngas), respectively [6]. Thermal technologies used to recover energy from solid waste are generally classified as either conventional combustion or advanced thermal technologies [7]. Conventional combustion includes grate-fired and fluidized bed technologies. Despite the fact that fluidized bed technology is commonly applied, grate-fired technology is preferred when it comes to small-scale application, handling of solid fuels that have varying or even higher moisture content and it does not require extensive pre-processing of the fuels. Energy recovery is achieved through the production of steam in boiler super-heater tubes. The steam may be utilized to generate electricity in a steam turbine generator or sold directly for commercial or process heat purposes. The heat content of steam exiting the steam turbine generators can also be used for district heating purposes.

The utilization of biomass for electricity generation has already been established, for example in Sweden in 2010 there were 32 waste-to-energy (WTE) plants. These plants combust an estimated 5.1million tonnes of solid waste generated annually to produce about 1.6TWh of electricity per year and a clean environment for her citizens to live in [8]. In Nigeria about 25 million tonnes of solid waste are generated annually [9]. With about 14million tonnes available for combustion in WTE plants [10], these solid wastes could generate about 4.4TWh of electricity per year and their combustion in this manner could assist in the effort to provide an aesthetic environment in the country. The electricity generated would greatly complement the current grid electricity, reduce the number of hours that electricity is unavailable and boost economic activities in Nigeria. Adopting WTE technology in Nigeria would contribute to achieving the goals of Nigeria's Renewable Energy Master Plan (REMP), which is to have biomass-based power plants with installed capacity of 50MW in 2015 and 400MW in 2025 [11]. WTE technology could portend electrical energy independence for most private companies and tertiary institutions that before now have to spend huge extra sums of money on diesel generators despite already paying huge amount for grid electricity. With the power sector now privatized, WTE technology could present the generation companies a cheap alternative source for generating electrical energy. Additionally, the streets of Nigeria will be cleaner and healthier by combusting her solid waste in WTE plants.

According to [12], about 19 thousand tonnes of solid waste are generated annually in Benin Metropolis. With the grate-fired technology, about 6.1GWh could be harnessed annually from this quantity of waste. This quantity of electrical power would contribute hugely to satisfying the electricity need of Benin Metropolis. Such solid waste utilization would enhance cleanliness in the metropolis. This paper presents thermal analysis of a steam boiler with feedstock from combustible solid waste.

2. METHODOLOGY

2.1 Daily Municipal Solid Waste Generation in Benin Metropolis

Table 1 shows the average daily solid waste generation in Benin metropolis. According to [13], population of Benin Metropolis is 1,085,676 . Therefore, total solid waste generated per day = 0.358 × 1,085,676 = 388, 672.008kg and total combustible solid waste per day = 0.049 × 1,085,676 = 53,198.124kg.

2.2 Combustion Analysis of Municipal Solid Waste (MSW)

Municipal solid waste 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. $c + h + 0 + n + s + m + a = 1$kg of fuel (MSW) [14].

Water and nitrogen are found in gaseous form after combustion. The ash does not participate in the combustion process. The oxygen contained in the fuel gives a negative contribution to the demand of oxygen for combustion. The theoretical combustion reaction formulae of the combustible elements of municipal solid waste are expressed by the following equations:

$$C + [O_2 + (79/21)N_2] \rightarrow CO_2 + (79/21)N_2 \quad (1)$$

$$H_2 + 05[O_2 + (79/21)N_2] \rightarrow H_2O + 0.5\,(79/21)N_2 \quad (2)$$

$$S + [O_2 + (79/21)N_2] \rightarrow SO_2 + (79/21)N_2 \quad (3)$$

The mass balance in the combustion chamber can be expressed as shown in Figure 1 in the form:

$$\dot{m}_{in} = \dot{m}_{out} \quad (4)$$

Table1: Average components of household solid waste generated per person per day.

Components	Mass(kg)
Food waste	0.281
Plastic/rubber	0.031
Paper	0.015
Metal waste	0.012
Glass	0.008
Other waste	0.003
Total Solid Waste	0.358

Source *[12]*

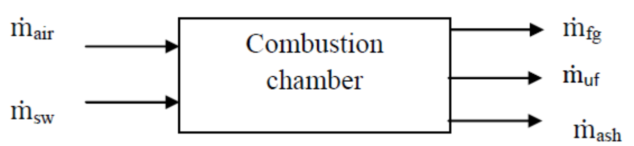

Figure 1: Mass balance in the combustion chamber.

$$\dot{m}_{sw} + \dot{m}_{air} = \dot{m}_{fg} + \dot{m}_{ash} + \dot{m}_{uf} \quad (5a)$$

$$\Rightarrow \dot{m}_{air} = (\dot{m}_{fg} + \dot{m}_{ash} + \dot{m}_{uf}) - \dot{m}_{sw} \quad (5b)$$

$$\dot{m}_{fg} = (\dot{m}_{sw} + \dot{m}_{air}) - (\dot{m}_{ash} + \dot{m}_{uf}) \quad (5c)$$

Amount of theoretical air $(\dot{m}_{air}{}^{th})$ can be calculated as follows:

$\dot{m}_{air}{}^{th}$ = O_2 required per kg of solid waste/ 23.3% of O_2 in air, where, air is assumed to contain 23.3% of O_2 by mass.

$$\frac{\frac{c}{12.01} + \frac{0.5h}{2.016} + \frac{s}{32.06} - \frac{o}{32}}{0.233} \quad (6a)$$

$$= 0.357c + 1.064h + 0.134s - 0.134o \quad (6b)$$

Substituting eqn. (7) into eqn. (5c), the mass of flue gas per kg of solid waste can be obtained as follows:

$$\frac{\dot{m}_{fg}}{\dot{m}_{sw}} = (0.357c + 0.134s - 0.134o) + \left(1 - \frac{\dot{m}_{ash}}{\dot{m}_{sw}} - \frac{\dot{m}_{uf}}{\dot{m}_{sw}}\right) \quad (7)$$

With excess air,

$$\frac{\dot{m}_{air}}{\dot{m}_{sw}} = (1+\alpha)(0.357c + 1.064h + 0.134s - 0.134o) \quad (8)$$

and

$$\frac{\dot{m}_{fg}}{\dot{m}_{sw}} = (1+\alpha)(0.357c + 1.064h + 0.134s - 0.134o) + \left(1 - \frac{\dot{m}_{ash}}{\dot{m}_{sw}} - \frac{\dot{m}_{uf}}{\dot{m}_{sw}}\right) \quad (9)$$

Where, (1+α) is the excess air ratio.

3. CALCULATION OF COMBUSTION AIR AMOUNT

Nitrogen reacts with oxygen to form NO_x at about 1200°C and above [15]. In this study, the upper limit of flue gas temperature is assumed as 1150°C. So, nitrogen is not considered to react with oxygen during the combustion reaction. It limits the intimacy between the fuel molecules and oxygen [15]. Table 2 shows the ultimate analysis of the combustible fraction of MSW.

Considering the theoretical combustion reaction for the elemental analysis of MSW, yields

C	+	O_2	→	CO_2	(10)
12.01kg		32.00kg		44.01kg	
0.47025kg		1.25296kg		1.72321kg	
H_2	+	$0.5O_2$	→	H_2O	(11)
2.016kg		16.00kg		18.016kg	
0.05175kg		0.41071kg		0.46246kg	
S	+	O_2	→	SO_2	(12)
32.06kg		32.00kg		64.06kg	
0.0009kg		0.0008983kg		0.0017983kg	

Assuming 30% excess air,

$$\dot{m}_{air} = m_{air}{}^{th}\,(1+\alpha) \quad (13)$$

The calorific value of MSW was calculated using Dulong's formula [17] and elemental analysis of MSW given in Table 2.

$$CV_{sw} = 0.339C + 0.105S + 1.21(H - 0.125O) - 0.0251H_2O \quad (14)$$

4. BOILER CALCULATIONS

4.1. Boiler Efficiency

There are two methods of calculating boiler efficiency: the direct and indirect methods [18].

Table 2: Ultimate analysis of MSW on a percentage by mass

Element	C	H	S	O	N	Moisture	Ash
Percentage	47.025	5.175	0.09	29.700	1.620	10.000	6.390

Source [16]

In the direct method, the boiler efficiency is directly defined by the useful heat output from the boiler and the heat input to the boiler obtained by burning fuel; it is expressed as [18]:

$$\eta_b = \frac{Q_s}{Q_f} \quad (15)$$

The indirect method determines the efficiency of a boiler by the sum of the major heat losses and the heat input to the boiler as expressed below [18]

$$\eta_b = 1 - \frac{Q_{losses}}{Q_f} \quad (16)$$

Though, the indirect method provides a better understanding of the effect of individual losses on the boiler efficiency [18], the direct method was used in this work to determine the boiler efficiency due to insufficient information on the actual losses in the boiler being analysed. From (16),

$$Q_s = \dot{m}_s\,(\alpha_s - \alpha_w) \quad (17)$$

and

$$Q_f = \dot{m}_{sw} CV_{sw} \quad (18)$$

4.2 Furnace Heat Flux

The average heat flux,q, in the furnace is given by [14]

$$q = \frac{Q_s}{A_f} \quad (19)$$

4.3 Equivalent Evaporation of Boiler

This is the amount of water evaporated at 100°C, forming dry and saturated steam at 100°C at normal atmospheric pressure. As the water is already at the boiling temperature, it requires only latent heat at 1.013bar to convert it into steam at 100°C. The value of this latent heat is taken as 2257kJ/kg. Thus, the equivalent evaporation, E, of a boiler from and at 100°C is given by [18]

$$E = \frac{\dot{m}_r(\alpha_s - \alpha_w)}{2257} \quad (20)$$

In (20), $\dot{m}_r = \dot{m}_s / \dot{m}_{sw}$ and $(\alpha_s - \alpha_w)/2257$ is known as factor of evaporation, and its value is always greater than one for all boilers.

4.4 Electrical Power Generation

The temperature – entropy (T – s) diagram for the processes in the solid waste steam boiler (SWSB) power plant is shown in Figure 3.

Pressure of steam at turbine inlet, p_4 = 20bar (given), Temperature of steam at turbine inlet, t_4 = 400°C (given), Pressure of steam at turbine outlet, p_5 = 0.1bar (assumed). Specific enthalpy and entropy of steam at turbine inlet are obtained from [19]:

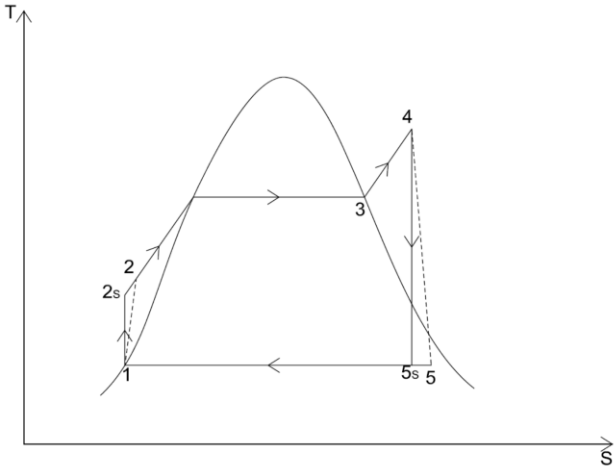

Figure 2: T-s diagram of the SWSB plant.

$$S_{5s} = f_{f5} + x_{5s}.S_{fg5} \quad (21)$$

Where, x is the dryness fraction of the steam.
Similarly,

$$h_{5_3} = h_{f5} + X_{5_3} h_{fg5} \quad (22)$$

$$\eta_{ti} = \frac{h_4 - h_5}{h_4 - h_{5s}} \quad (23)$$

In (27), h_5 is actual enthalpy of steam at turbine outlet. Small, single stage steam turbines can have efficiencies as low as 50% [21]. Thus η_{ti} is assumed to be 0.5.

$$W_t = h_4 - h_5 \quad (24)$$

Ideal pump work is given by:

$$W_p = \frac{P_2 - P_1}{\rho_f \times \eta_p} \quad (25)$$

The electrical power obtainable from the produced steam is given by [20]:

$$P_e = m_s(\dot{W}_t - \dot{W}_p) \times \eta_m \times \eta_{gen} \quad (26)$$

5. RESULTS AND DISCUSSION

The parameters used and those obtained by utilising the thermal analysis equations are presented in Table 3. The variation of the calorific value of solid waste with different values of moisture content is shown in Figure 3.

Table 3: Parameters used and those obtained from the thermal analysis equations

Mass flowrate (kg/s)		Enthalpy/ Work (kJ/kg)		Temperature (°C)		Heat (kW)	
$\dot{m}_{sw}$	1.000	α_s	3248.000	T_{fgi}	705.000	Q_f	17490.000
$\dot{m}_{air}$	7.630	α_w	194.490	T_{fgo}	200.000	Q_s	10494.914
$\dot{m}_{fg}$	8.566	α_e	2752.865	T_s	400.000	Power (kW)	
$\dot{m}_s$	3.437	$\dot{W}_t$	495.135	T_w	46.036	P_e	1351
		$\dot{W}_p$	2.513				
Efficiency (%)							
η_b	60	η_{tm}	84	η_{ti}	50	η_p	80
η_{gen}	95						
Other Parameters							
CV_{sw} [kJ/kg]	17490	E	4.6499	Cp_{fg} [kJ/kgK]	1.3067	q(kW/m²)	6996.609
p (bar)	0.1	A_f [m²]	1.5000				

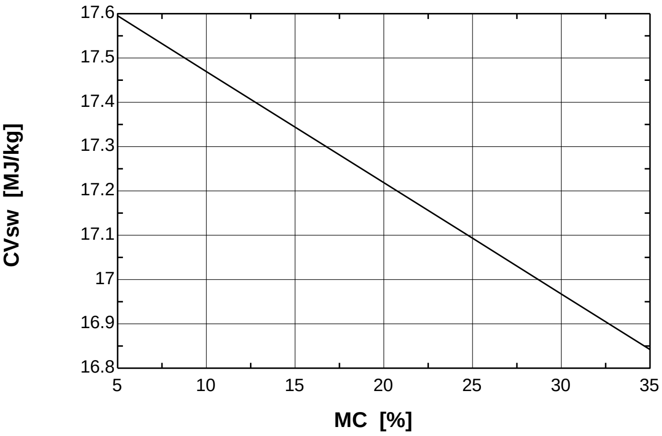

Figure 3: Variation of calorific value of the solid waste with different values of moisture content.

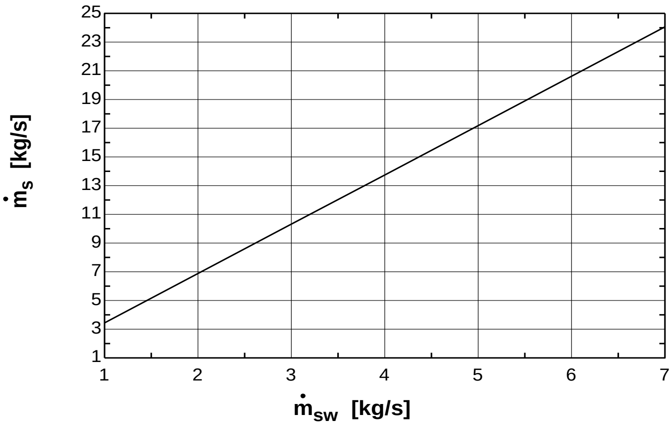

Figure 4: Changes in the quantity of steam generated in relation to amount of solid waste combusted.

The drying characteristics of solid waste depend on their moisture contents. Those with higher moisture content require longer time and more energy to dry them, thereby reducing the amount of heat available from the waste and thus resulting in lower temperature in the furnace.

The reverse is the case for solid waste with lower moisture content. If the moisture content is too high, the furnace temperature achieved will be too low to sustain combustion, hence an auxiliary fuel will be needed to raise the temperature and ensure normal combustion. To evaluate the effect of moisture on the combustion process, numerical simulation and analysis were carried out using seven different values of moisture content. The Engineering Equation Solver (EES) developed at University of Wisconsin was used for the analysis. The results of the analysis show that the lower the moisture content in solid waste the higher its heating value and hence higher temperatures in the furnace. Hence, for better boiler efficiency, the solid wastes should be dried before being fed into the furnace. Figure 4 shows the changes in the quantity of steam generated in relation to the amount of solid waste combusted. The quantity of heat energy generated when solid waste is combusted depends directly on the amount of solid waste combusted for a constant calorific value of the solid waste. Equation (16) indicates that the greater the amount of solid waste combusted the greater the quantity of heat released, hence, the higher the furnace temperature and vice versa. The high furnace temperature thereby influences the quantity of steam generated in the boiler. Numerical simulation and analysis carried out with seven different amounts of solid waste show that, for the chosen design specifications, the quantity of steam generated increases with increase in the amount of solid waste combusted.

Ultimate analysis of a waste stream need to be performed before the theoretical/actual amount of air required to combust the waste stream can be determined. The ultimate analysis of municipal solid waste from Port Harcourt Metropolis was carried out by [16] and the values are presented in Table 2. Benin and Port Harcourt are cities with similar culture and from the same geographical location in Nigeria; it is assumed that both cities have similar composition of municipal solid waste stream. Hence, these values can reasonably be assumed for municipal solid waste from Benin Metropolis.

The steam produced in the boiler may be utilized to generate electricity in a steam turbine generator. Several assumptions were made to account for losses in the turbine and alternator during the numerical calculations. Results from the analysis reveal that about 1.4MW can be generated from the combustion of 3.6ton/hr of solid waste, indicating that, based on the design specifications, about 20.7MW of electrical power could be generated from the solid waste generated per day in Benin Metropolis. US Energy [22] has published data concerning the amount of fuel that can be efficiently used to generate 1kWh of electricity. For the case of solid fuel like coal, 0.13104kg/s of it can be used to generate 1MW of electricity. With the epileptic power supply in Nigeria, this quantity of electrical power would complement that generated in the country. Such a process of energy recovery from waste will contribute to waste management in Benin Metropolis as about 14% of the daily generated solid waste would have been converted to energy thereby reducing the volume of solid waste left for disposal.

6. CONCLUSION

This paper presents a thermal analysis of a small-scale steam boiler with feedstock from combustible solid waste for electrical power generation. Energy balance relations were derived and analysed based on the design specifications. Results from the analysis show that the calorific value of the solid waste varies with the percentage of moisture content of the combustible solid waste, and that the quantity of steam generated varies with the amount of solid waste combusted. However, a calorific value of 17.49MJ/kg obtained at a moisture content of 10% was used for analysis in this work. This indicated that about 3.437kg/s of steam at 20bar and 400°C can be obtained from the combustion of 3.6ton/hr of solid waste. The produced steam can be utilized for electrical power generation and, about 1.4MW of electrical power was obtained from calculation. It was observed that the process of combusting solid waste with energy recovery reduces the waste stream available for disposal by about 14%.

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