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Predicting the Quantity of Municipal Solid Waste Required for Power Generation Using Power Plant Design Parameters

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Abstract-
In energy recovery technology, via municipal solid waste (MSW) as an energy resource; the capacity of the power plant required can be designed, if the potentials of the heat and electrical energy of the waste to be combusted has been established. Conversely, in this research, the amount of power potential of the waste required as fuel, is determined through the design for the capacity of the steam power plant that will utilize municipal solid waste as an energy resource. The capacity of the power plant is designed, using single reheat Rankine cycle. The pressure and temperature selected for the design of the boiler is 30 bar and 400 ^{0}C, the pressure at the reheat tube is 6 bar, and the pressure at the condenser is 0.032 bar. The heat supplied to the boiler is calculated to be 3639.2 kJ/kg, the total work-output of the turbine is 1451.4 kJ/kg and the heat rejected at the condenser is 2187.6 kJ/kg. The quantity of MSW required is predicted to be 418 MJ/kg based on the calorific value of 20 MJ/kg, and its heat energy and electrical power potentials is predicted to be 2.3 GWh and 29 MW respectively while the grid to power is 20 MW.

Key words: Energy recovery, heat energy and electrical power potentials

1. Introduction

Municipal solid waste (MSW) production is a constant phenomenon in the daily activities of man as he interacts with his environment [1]. During the stone age, materials which include bones and horns; skins of animal and leaves; sheaf, raffia, bamboo and wood; were the materials used for weapons, clothing and shelters respectively; thereby making the major waste generated then, to be wastes from plants and animals. Demographic growth, urbanization, industrialization and the need for new materials, cause the pattern and trends of MSW generation to change, and the rate of generation increases on daily basis [2]. According to [3], municipal solid waste (MSW) is referred to as discarded materials which include food residues, bottles, packaging box, cans, rags, grass and garden trimmings, damaged furniture, papers, electronics and electrical appliances; that are generated by man as he interacts with his surrounding on daily activities.

Municipal solid waste management (MSWM) is defined [4], as a systematic method by which activities involved in planning, storing, collecting, transporting, processing and disposal of MSW are coordinated and funded. [2] stated that the most effective and sufficient method of waste management, is the energy recovery option; according to [5], WTE option, will serve a dual purpose of efficient waste management and energy recovery for heating and power generation. For a sustainable WTE power plant to be put in place, it is necessary to determine how available and sustainable the MSW is. Moreover, the energy content of the MSW, as well as its efficiency in terms of energy and electrical power potentials must be established.

Nevertheless, the physicochemical characteristics of the waste is essential to be able to determine the correlation between them and the hating value [5].

The capacity of the bio-waste fired power plant to convert the waste to electrical power can be determined if the quantity of MSW available for energy generation and its heating value are known. Conversely, the quantity of waste required to be converted to energy, can be established by first determining the capacity of the required power plant, if the expected steam mass flow rate of the plant boiler is selected. The electrical power potential of the required MSW is determined using the steam flow rate of the power plant, then the heating value, and the power potential of the waste are input into the power potential mathematical model to obtain the quantity of the waste required for power generation. In this study, the heating value facts and figures of the MSW characterized by [5], at Lasoju dumpsite of Ilorin metropolis is adopted for the analysis. The waste-to-energy (WTE) system envisaged in predicting the amount of MSW to be converted, is incineration of MSW as solid fuel, to produce steam in a boiler to drive the turbine of a power plant; which drives a generator connected to it through a shaft to produce electricity.

1.1. Energy generation via MSW

Renewable energy can be produced using MSW as a resource. The municipal solid waste (MSW) fractions that are neither reused nor recycled, can be converted into fuel, through processes like anaerobic digestion, combustion, pyrolization, gasification, and landfill gas (LFG) recovery. This fuel can be used to generate heat and electrical energy, which are of economic value. The type of technological method to adopt in recovering energy from the waste fractions, depends on the composition of the waste streams, category of waste fractions most prominent and its availability, the physicochemical characteristics of the waste, its energy potential and the expected output of the recovery. [2],[5]; both reported that WTE is an optimal method for providing a sustainable solution, to waste management problems while harnessing its hidden energy [6].

Technologies are available for the conversion of solid waste to energy (WTE). They include production of gas from sanitary landfill, gasification, incineration, pyrolysis, anaerobic digestion, and other types. In sanitary landfill method, the solid waste is scientifically dumped, and the waste components can decompose to release gas; which can be collected for energy generation. Incineration technology involves the combustion of MSW in a controlled environment by channeling the heat generated; to produce steam which is used produces power in steam turbines. In gasification method of WTE technology, MSW is first pyrolysed under limited air, low molecular weight gases are then generated through pyrolysis at higher temperature reactions. These gases could be burned for steam generation in boilers to produce power using steam turbines; it can also be used in internal combustion engines [7]. In bio-methanation, digestion of the putrescible fractions of waste, takes place in a specially designed digesters under the activity of active bacterial; methane and inert carbon-dioxide gases are produced from the digested pulp. The remaining digestate could be used for soil conditioner. Other technologies used are palletization, pyro-plasma, and flash pyrolysis.

The incineration technology involves combusting the waste to produce heat energy that will produce steam in the seam boiler of a power plant to drive the steam turbine which then drives the shaft connected to generator to generate electricity. The choice of technology is a function of the components of waste to be used as fuel, its availability and efficiency, and some environmental conditions. The most appropriate option would be the technology that is of low cost, that requires moderate area of land and generate less pollution while reducing the volume of waste [8].

2. Methodology

The process involves sorting and characterization of municipal solid waste into component fractions, determination of the heating value, establishing the energy and electrical power potentials of the waste, and determination of the power plant capacity required. Using the steam mass flow rate of the plant, and the energy power potential of the MSW, the quantity of the waste needed for energy production predicted.

2.1. Physical Characterization of the MSW Streams

The waste generated in Ilorin was characterized for eight months by [5] based on American Society for Testing and Materials (ASTM D5231). Sixty-two samples of 240 litres bin volume of MSW each was collected. Each sample was poured into a screening and sieving table of 1.5m x 3 m with 10 mm x 10mm mesh surface size, shown in Fig. 1, designed to sort non-homogeneous waste components [9], [2]. The waste was sorted into different fractions in different receptacles. The weight and corresponding volume were recorded. Nineteen fractions were characterized namely: paper, carton, grass/trimmings, textile (rags), toiletries, cow-dungs, excrement, ceramics/glass, tins/metals, food-residue, wood, nylon, polythene-sac, plastic-bottle, rubber, bones, leather, sand/ash and others.

Fig. 1: The researcher sorting MSW fractions on the Screening-Table.

2.2. Determination of the Calorific Value (CV) of the Waste Fractions

The calorific (heating) value of the MSW was determined using an *e 2k* bomb Calorimeter as shown in Fig. 2, in accordance to the standard ASTM D5468-02 [1].

Fig. 2: ***e 2k*** **Combustion Calorimeter**

According to [10], [2], low heating value (LHV) used in energy content determination is obtained from the high heating value (HHV) of waste fractions using equation 1:

$$LHV = \sum_{1}^{9} W_{\mathrm{j}} \times HHV_{\mathrm{j}} \quad (1)$$

Where LHV is the low calorific (heating) value, HHV_{j} is the high calorific value of MSW component- j and W_{j} is the percentage weight fraction of component- j [10].

2.3. Design of Steam Power Plant Capacity, Required for the Power Generation

In this section, the power of the steam boiler, steam turbine and the condenser was determined; using Rankine cycle.

2.3.1. Steam Rankine cycle

The heat recovery boiler and the steam turbine operation are based on thermodynamic processes called "Rankine cycle", shown in Fig. 3. Where the expansion to lower pressure and temperature of the hot steam exhaust takes place in turbine for power generation [11].

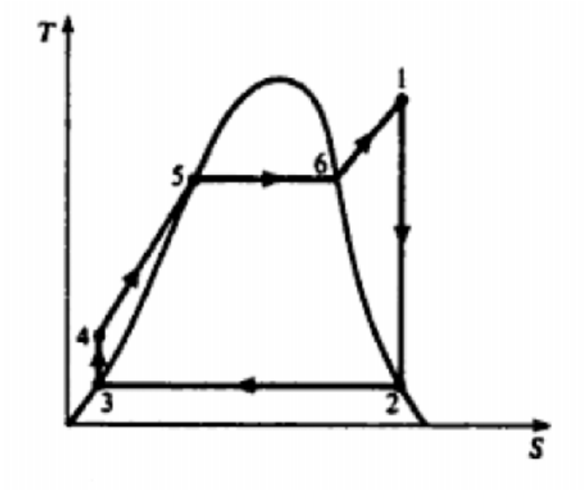

Fig. 3. T-S Diagram for a Rankine-cycle with Superheat

2.3.2 Rankine Cycle with reheat process

The reheat Rankine cycle in Fig. 4, is a modification of simple Rankine cycle shown in Fig. 3 shown as the Temperature-entropy (T-S) diagram.

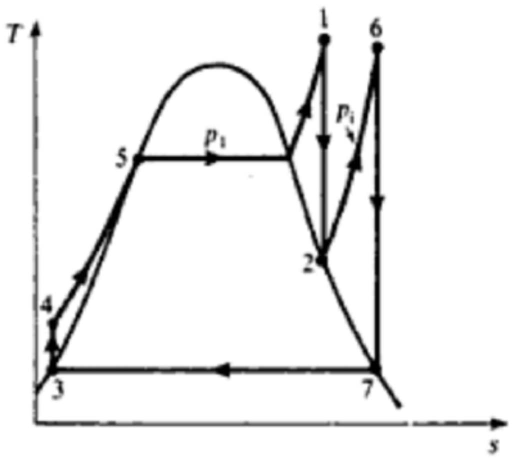

Fig. 4. T-S Diagram for a reheat Rankine Steam Power Plant cycle.

The temperature and pressure selected for the design of the power plant steam generation in the boiler, is 400 ^{o} C and 30 bar; because temperature higher than 400 ^{o} C, may cause high temperature corrosion and strain in the boiler steel alloy super heater tubes [12], [13]. The steam mass flow rate selected is 20 kg/s (72 tons/h).

2.3.3 Processes in the Reheat Rankine Cycle

i. Process (1-2): This is an isentropic process from node 1 to node 2 in Fig. 2. The work output ($W_{T_{12}}$), of the high-pressure turbine (HPT) is calculated in equation 2, according to [14], [15].

$$W_{T_{12}} = h_1 \; h_2 \quad (2)$$

Where $W_{T_{12}}$ is the work output in kJ/kg, h_1 and h_2 are the enthalpy at nodes 1 and 2 respectively.

ii. Process (2-6) is the reheat process of the steam in the boiler reheat-tube, at pressure of 6 bar. The heat Q_{26}, supplied during this process, according to [14], [15]. is calculated in equation 3:

$$Q_{26} = h_6 - h_2 \quad (3)$$

iii. Process (6-7), is an isentropic process within the low-pressure turbine (LPT) from node 6 to node 7. At node 6, after the steam has attained the required temperature 400 ^{0} C, it passes through the low-pressure turbine for the second expansion. In equations 4 and 5, h_7 and S_7 are the enthalpy and entropy at the inlet of the condenser while x_7, is the dryness fraction.

$$S_6 = S_7 = 7.571 \text{ kJ/kg K (isentropic expansion).}$$

But $$S_7 = S_{f_7} + x_7(S_{g_7} - S_{f_7}) \quad (4)$$

Also $$h_7 = h_{f_7} + x_7(h_{g_7} - h_{f_7}) \quad (5)$$

The work output at the low-pressure turbine, $W_{T_{67}}$ is given in equation 6, according to [16].

$$W_{T_{67}} = h_6 - h_7 \quad (6)$$

The total work output of turbine (both H.P. turbine and L.P. turbine), (W_T)

$$(W_T) = (W_{T_{12}} + W_{T_{67}}) \quad (7)$$

iv. Process (7-3), is the condensation process of the steam in the condenser from node 7 to node 3 of the Rankine cycle. The heat rejected Q_{37}, during this process is calculated using equation 8, according to [16].

$$Q_{37} = h_7 - h_3 \quad (8)$$

Neglecting pump work, the heat supplied into the boiler Q_{13} is calculated in equation 9, as suggested by [16], [17].

$$Q_{13} = h_1 - h_3 \tag{9}$$

The Total heat (Q_B) supplied by the boiler to the steam, is calculated as the addition of heat Q_{13} and Q_{26} of reheat, in equation 10; according to [15], [17].

$$Q_B = Q_{13} + Q_{26} \tag{10}$$

$$\text{Net heat supplied } (Q_{net}) = (Q_{13} + Q_{26}) - Q_{37} \tag{11}$$

2.3.4. Estimation of the power plant capacity

i. *The electrical power potential (EPP_{msw})*

The electrical power potential (EPP_{msw}) of the municipal solid waste (MSW) that will fire the steam power plant is calculated using equation 12, as suggested by [14, [16]

.

$$(EPP_{msw}) = \dot{m}_s \times Q_{net} \tag{12}$$

Where EPP_{msw} is the electrical power potential of the MSW, taken to be the capacity of the steam power plant [5]; $\dot{m}_s$ is the selected steam mass flow rate (20 kg/s) and Q_{net} is the net heat supplied.

ii. *MSW consumption rate, m_f*

Assuming efficiency (η_B) of 80 % for the boiler [18]. The MSW consumption rate (m_f) as solid fuel, is calculated in equation 13, as suggested by [14].

$$\text{MSW consumption rate, } m_f = \dot{m}_s\left[\frac{(h_1 - h_3) + (h_6 - h_2)}{\eta_B \times LHV}\right] \tag{13}$$

Where m_f is the fuel consumption rate, η_B is the boiler efficiency, and LHV is the low heating value of MSW.

iii. *Boiler power (Q_{BP})*

The power generated by the boiler per day for the Steam Power Plant, using MSW is given in equation 14.

The boiler power, $Q_{BP} = \dot{m}_s \times Q_B$ (14)

iv. *Turbine power* (P_T)

The power from the Turbine of the steam power plant is calculated in equation 15:

The turbine power $(P_T) = \dot{m}_s \times W_T$ (15)

The power output from Turbine is the same as the electrical power potential obtained while using the available MSW selected for power generation [5]

v. The Condenser Power (Q_{PC})

This is the daily power exerted by the condenser in the steam power plant. This is the product of heat rejected from the condenser and the steam mass flow rate as calculated in equation 16.

The Condenser Power $(Q_{PC}) = \dot{m}_s \times Q_C$ (16)

2.3.5. Determining the quantity of waste required by the power plant per day for power generation

i. *The electrical power potential (EPP_{msw})*

The electrical power potential $(EPP_{msw}) = LHV_{msw} \times \frac{w_{msw}}{24} \times \frac{1000}{3.6} \times \eta$ (kW) (17)

Where η is the conversion efficiency in a power plant, which is within a range of 20-40% as adopted by [19]. However, a conversion efficiency of 30% is adopted for this work.

ii. *The quantity of municipal solid waste w_{msw}*

The quantity of municipal solid waste $w_{msw} = \frac{EPP_{msw}}{LHV_{msw}} \times \frac{3.6}{1000} \times \frac{24}{\eta}$ (kg) (18)

Where W_{msw} (tons) is the weight of MSW required, EPP_{msw} is the electrical potential of the MSW (kW), LHV_{msw} is the net low heating value of the MSW (MJ/kg). Conversion ratios (3.6 MJ = 1kWh; 1 day = 24 h and 1 ton = 1000 kg)

iii. *The heat energy potential of MSW*(EP_{msw})

The heat energy potential of MSW$(EP_{msw}) = LHV_{msw} \times w_{msw} \times \frac{1000}{3.6}$ (kWh) (19)

iv. *Power to grid* (GP)

Power to grid $(GP) = EPP_{msw} \times \eta_g \times \eta_P \times \frac{1}{1000}$ (MW). (20)

Where η_g is the generator efficiency (selected is 90 %), η_p is the transmission efficiency (selected is 75 %) of turbine work (W_T). Generator efficiency range is 85- 90 % and turbine efficiency is within a range of 75-80 % [18].

3. Result and discussions

3.1. *Physical and thermal Characterization of MSW.*

The combustible MSW fractions that are selected for energy production, out of the nineteen waste fractions identified, is presented in Table 1, showing their percentage distribution by weight and their corresponding heating values. The fractions with percentage heating value ≥ 16 has high percentage content of fixed carbon and total carbon from proximate and ultimate analysis [2].

Table 1. the thermo-chemical analysis of the waste components for energy Production.

S/N	Waste fractions	Wt. kg	HHV (MJ/kg)	Mean	HHV%	Wt.%	LHV (HHV*Wt.%)
1	Food residue	318.5	18.624	18.6±0.54	8.24	10.37	1.9313
2	Wood	24.70	18.418	18.4±0.03	8.13	0.80	0.1473
3	Paper	185.7	17.038	17.0±0.92	7.52	6.04	1.1291
4	Packaging box	29.,6	15.883	15.8±1.20	7.03	9.69	1.5391
5	Grass/Trimmings	137.2	17.838	17.8±0.25	7.86	4.47	0.8974
6	Nylon	467.8	46.160	46.1±0.24	20.4	15.23	7.1302
7	Textile (rag)	273.8	15.747	15.7±2.83	6.92	8.91	1.4031
8	Polythene sac	163.5	39.352	39.3±0.65	17.4	5.32	2.1935
9	Plastic bottle	300.7	37.282	37.2±0.73	16.5	9.79	3.6499
	Total	1871.9	226.32		100	70.62	20.02

3.2. *The Parameters at each state in the Power plant cycle and the Capacities of the Power Plant Components*

The parameters determine for each node (state) during the thermodynamic processes required in the Rankine reheat cycle for the design of steam power capacity is given in Table 2, and the design capacities for each equipment of the power plant required, is given in Table 3.

Table 2. The Parameters Determined for the Nodes of the Steam Power Plant Cycle

Description	Node	Pressure (bar)	Temp. (° C)	Enthalpy (KJ/kg)	Entropy (kJ/kg K)
Boiler outlet /H-P turbine inlet	1	30	400	3231	6.921
H-P turbine outlet / Intermediate superheater inlet	2	6	158.8	2757	6.761
Intermediate superheater outlet / L-P turbine inlet	6	6	400	3270	7.707
L-P turbine outlet/ condenser inlet	7	0.032	25		
Condenser outlet / pump inlet	3	0.032	25	104.8	0.367
Pump outlet / boiler inlet	4	40	205	875	2.382

Table 3. The Capacities designed for the Steam Boiler Power Plant Components

Equipment	Heat (kJ/kg)	Work (kJ/kg)	Power (MW)
Boiler	3639.2	-	73
Turbine	-	1451.35	29
Condenser	2187.85	-	44
Steam and Fuel Consumption Rate of The Plant			
Water/ Fuel Consumption	kg/s	(tons/h)	(kg/kWh)
Steam mass flow rate ($\dot{m}_s$)	20	72	
Fuel consumption rate (m_f)	6.25	45.49	
Specific steam consumption (SSC)			2.48

3.3. Estimated Energy and Electric Power Generation from MSW

The estimated energy and power potentials of the MSW based on the quantity of MSW determined for energy generation per day and their net heating value is presented in Table 4.

Table 4. The predicted energy and power potentials of the Municipal Solid Waste

1	W_{MSW} $(tons/day)$	LHV (MJ/kg)	EP_{MSW}(MWh)	EPP_{MSW} (MW)	GP (MW)

	418	20	2322	29	20
2	Conversion ratio 1000 kg = 1 ton	10^6J = 1MJ	1kWh = 3.6 MJ	η = 30%	η_g= 90% and η_p= 75%

4. Conclusion

It is established in this study, that the quantity of municipal solid waste (MSW) that is needed for power generation, could be determined when designing the capacity of the steam power plant that will convert the waste. Using the heating value of 20 MJ/kg of the waste, in a steam power plant of 20 kg/s (72 tons/h) steam mass flow rate, having pressure and temperature conditions of 30 bar and 400 ^{0} C in the boiler; pressures of 6 bar and 0.32 bar in the reheat tube and condenser respectively. 418 tons of combustible MSW will produce energy potential of 2,322 MWh, electrical power potential of 29 MW and grid to power of 20 MW. The boiler power of the plant is determined to be 73 MW, turbine power while neglecting the pump work is 29 MW and the condenser power is 44 MW.

3. Recommendation

Waste recovery system via incineration technology is appropriate for Ilorin metropolis, because the combustible MSW fractions is about 71% of the aggregate municipal solid waste generated and the power potential of the waste predicted (29 MW), can solve about 11 % power demand in Kwara state (Ibikunle et al., 2019).

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