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EFFECTIVE UTILIZATION OF A SMALL-SCALE MUNICIPAL SOLID WASTE FOR POWER GENERATION

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ABSTRACT

Quantity of small scale municipal solid waste available in each of the states of Nigeria was assessed and determined. Physical and Chemical characteristics of the various types of solid wastes were analysed and their values estimated. Thermal analysis of a small-scale municipal solid waste-fired steam generator was done. The analysis was based on the selected design parameters: operating steam pressure of 10 bar, with fuel consumption rate of 500 Kg/h and combustion chamber which utilizes mass burn incineration using water wall furnace. The plant is designed as a possible option for thermal utilization of rural and urban wastes in Nigeria. The average daily generation of MSW was considered in order to assess the availability of the material. The data were collected from Enugu State Waste Management Authority **(***ENSWAMA).This was calculated based on the state population, urbanization and industrialization strengths. Calculation of calorific value of the waste to determine the heat contents was carried out using two methods: Bomb calorimeter and Dulong's formula. Some samples of the garbage were analyzed with bomb calorimeter in the National Centre for Energy Research & Development Laboratory, University of Nigeria, Nsukka. The calorific values obtained from this analysis were 12572.308 KJ/kg, 14012.05 KJ/kg, 21833.26 KJ/kg and 20551.01 KJ/kg for paper products, woods, plastics and textiles waste respectively, while the energy content obtained from the elemental composition of waste using Dulong's formula was 15,101 KJ/kg .The maximum temperature of the furnace attained from the energy balance based on this value around the combustion chamber was 833.7 K and the amount of air required per kg of MSW was 8.66kg*

Keywords: Solid-waste, Steam, Temperature, Pressure, Moisture content, Calorific value

INTRODUCTION

Waste-to-energy facilities are part of the solution of the worldwide solid waste disposal problem. These facilities, when combined with recycling of critical material, composting, and land filling, will be a long-term economic solution as long as they are designed and operated in an environmentally acceptable manner.

As a result of high carbon dioxide, CO_2 emission from thermal energy conversion of fossil fuels which is one of the major causes of the greenhouse effect, boiler technologies based on biomass conversion represent a great potential to reduce CO_2 emission since they are based on the utilization of renewal energy source.

Furthermore, since conventional energy sources are finite and fast depleting and energy demand is on the increase, it is necessary for scientists and engineers to explore alternative energy sources, such as municipal solid waste (MSW).

Biomass is abundantly available on the earth in the form of agricultural residues, city garbage, cattle dung, but is normally underutilized. For an efficient utilization of these resources, adequate design of municipal solid waste- fired steam boiler is necessary in order to extract heat produced in the combustion of waste, considering the calculated high calorific value of MSW and the availability of this material around us. The environmental benefits of biomass technologies are among its greatest assets. Global warming is gaining greater acceptance in the scientific community. There appears now to be a consensus among the world's leading environmental scientists and informed individuals in the energy and environmental communities that there is a discernable human influence on the climate; and that there is a link between the concentration of carbon dioxide (one of the greenhouse gases) and the increase in global temperatures. Appropriate utilization of Municipal Solid Waste when used can play an essential role in reducing greenhouse gases, thus reducing the impact on the atmosphere.

In addition, some of the fine particles emitted from MSW are beneficial. Bottom and fly ash are being mixed with sludge from brewery's wastewater effluent treatment in a composting process, thus resulting in the production of a solid fertilizer. The possibility of selling the bottom and fly ash to the ceramics industry is also being considered, which increases the potentials of MSW fired steam boiler. (Adefemi and Awokunmi, 2009) in their work on this subject correlated the concentration of heavy metals in roots of plant from Igbaletere (in Nigeria) dump site with the concentration of heavy metals in the soil samples from the dump site. (Nabegu, 2010) found out that solid waste generated by households (62.5%) in Kano metropolis far out weighed that generated by various institutions in the same metropolis (5.8%). In the analysis of Municipal Solid

Waste management in Addis Ababa, (Nigatu Rigassa. *et al.*, 2011) observed that part of the reasons for low performance solid waste management was the inadequate and malfunctioning of operation equipment and open burning of garbage. This study thus seeks to analyse an efficient operating and burning system.

Combustion Analysis of Municipal Solid Waste (Msw)

Considering the theoretical combustion reaction for the organic component of the waste, such as carbon, hydrogen and sulphur, (Coskun *et al.*, 2009) gave the equation for stoichiometric combustion as :

$$C + (O_2 + \frac{79}{21}N_2) \rightarrow CO_2 + \frac{79}{21}N_2 \quad (1)$$

$$H + 0.25(O_2 + 3.76N_2) \rightarrow 0.5H_2O + 0.94N_2 \quad (2)$$

$$S + (O_2 + 3.76N_2) \rightarrow SO_2 + 3.76N_2 \quad (3)$$

It is known that nitrogen reacts with oxygen over about 1200^0C to form NO_x. In calculations, the upper limit of the flue gas temperature is assumed as 1200^0 C. Combustion process is assumed as in ideal case (Stiochiometric). So, nitrogen is not considered to react with oxygen during combustion reaction. It limits the intimacy between the fuel molecules and O_2 (Coskun *et al.*, 2009)

Table 1 shows the average daily generation of municipal solid waste in various states of Nigeria.

Table-1. Average daily generation of MSW in Nigeria

S/N	State	Metric Tonne	S/N	State	Metric Tonne	S/N	State	Metric Tonne
1	Abia	11	14	Enugu	8	27	Ogun	9
2	Adamawa	8	15	Gombe	6	28	Ondo	9
3	Anambra	11	16	Imo	10	29	Osun	7
4	Akwa-Ibom	7	17	Jigawa	9	30	Oyo	12
5	Balyesa	8	18	Kaduna	15	31	Plateau	9
6	Bauchi	9	19	Kano	24	32	Rivers	15
7	Benue	8	20	Kastina	11	33	Sokoto	9
8	Borno	8	21	Kebbi	7	34	Taraba	6
9	Cross River	9	22	Kogi	7	35	Yobe	6
10	Delta	12	23	Kwara	7	36	Zamfara	6
11	Ebonyi	7	24	Lagos	30	37	FCT	11
12	Edo	8	25	Nasarawa	6			
13	Ekiti	7	26	Niger	10			

(Source: ENSWAMA, MOE and NPC**)**

Complete combustion by using excess air can be expressed as follows:

$$C + (I + \lambda)(O_2 + 3.76CO_2) \rightarrow CO_2 + (I + \lambda)(3.76N_2) + \lambda O_2 \quad (4)$$

$$H + (I + \lambda)(O_2 + 3.76N_2) \rightarrow 0.5H_2O + (I + \lambda)(3.76N_2) + (0.75 + \lambda)O_2 \quad (5)$$

$$S + (I + \lambda)(O_2 + 3.76N_2) \rightarrow SO_2 + (I + \lambda)(3.76N_2) + \lambda O_2 \quad (6)$$

In combustion reaction, λ is the fraction of excess combustion air, having the relationship, n = (1+ λ)

where n is the excess air ratio and $\lambda = \frac{Actual\frac{A}{F}ratio - Stoichiometric\frac{A}{F}ratio}{Stoichiometric\frac{A}{F}ratio}$

The mass balance equation can be expressed as showed in figure 1 in the form as,

$m_{in} = m_{out}$ (7)

i.e. The mass of reactants is equal to the mass of products

$m_{fuel} + m_{air} = m_{flue\ gas} + m_{ash} + m_{mst}$ (8)

$m_{fluegas} = m_{air} + (m_{fuel} - m_{ash} - m_{mst})$ (9)

From Eqn. 8

$m_{air} = (m_{fluegas} + m_{ash} + m_{mst}) - m_{fuel}$ (10)

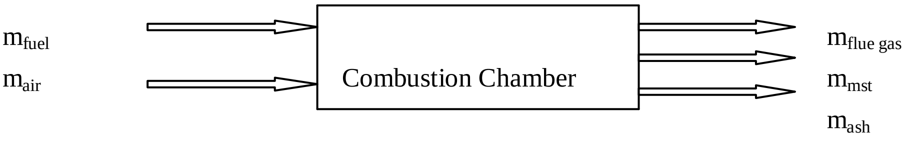

Fig-1. Mass balance in the Furnace

Stiochiometric air amount (n=1) can be calculated as follows;

$m_{air\ steo}$ = O_2 required per kilogram of the fuel/23.3% of O_2 in air

$= m_{O,H}K_H - m_{O,O}K_O + m_{O,S}K_S + m_{O,C}K_C/0.233$ (11)

Where $m_{O,H}$, $m_{O,O}$, $m_{O,S}$, $m_{O,C}$, are the masses of oxygen in hydrogen, oxygen, sulphur and carbon respectively.

$$m_{air,steo} = \frac{8K_H - K_O + K_S + \frac{32}{12}K_C}{0.233} \quad (12)$$

$$m_{air.Stea} = 34.3348K_H - 4.2918K_O + 4.2918K_S + 11.4449K_C$$

$$m_{air.steo.} = (3K_H - 0.3750K_O + 0.3750K_S + K_C)11.4449 \quad (13)$$

With excess air ratio,

$$m_{air} = (3K_H - 0.3750K_O + 0.3750K_S + K_C)(11.4449)(1+\lambda) \quad (14)$$

Where K denotes the percentage ratio of the element in chemical composition (in %) and m_{air} is the air requirement per kg fuel (kg air/kg fuel). Flue gas amount can be found by Eq. 9

Substituting Eq.13 in Eq. 9, knowing that calculations are done for 1 kg fuel, so the equation can be expressed as follows:

$$m_{fluegas} = (3K_H - 0.3750K_O + 0.3750K_S + K_C)(11.4449) + (1 - K_{ash} - K_{mst}) \quad (15)$$

Employing the excess air ratio,

$$m_{fluegas} = (3K_H - 0.3750K_O + 0.3750K_S + K_C)(11.4449)(1+\lambda) + (1 - K_{ash} - K_{mst})$$

(16)

Using the elemental composition of waste as shown in figure 1, the calculation of amount of air required and the flue gas produced can be done considering the above equations.

Table-2. Percentage by mass of MSW

Element	C	H	O	S	N	Moisture	Ash
percentage	35.5	5.1	23.9	0.5	2.4	25	7.6

(Source: P. Chattopadhyay, [5])

Calculation of Combustion Air Supply

Considering theoretical combustion reaction for the elemental analysis of MSW shown in table 2, we have,

Carbon (C):

$C+O_2 \rightarrow CO_2$

$12KgC+32KgO_2 \rightarrow 44KgCO_2$

Oxygen required = 0.355 * (32/12) = 0.947/Kg MSW (16)

Carbon dioxide produced = 0.355 * (44/12) = 1.302/Kg MSW (17)

Hydrogen (H):

$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

$2Kg\ H_2 + 16Kg\ O_2 \rightarrow 18Kg\ H_2O$

$1Kg\ H_2 + 8Kg\ O_2 \rightarrow 9Kg\ H_2O$

Oxygen required = 0.051 $\times$ 8 = 0.408 Kg/Kg MSW (18)

Steam produced = 0.051 $\times$ 9 = 0.459 Kg/Kg MSW (19)

Sulphur (S):

$S + O_2 \rightarrow SO_2$

$32Kg\ S + 32KgO_2 \rightarrow 64KgSO_2$

$1KgS + 1KgO_2 \rightarrow 2KgSO_2$

Oxygen required = 0.005 Kg/Kg MSW (20)

Sulphur dioxide produced = 2 $\times$ 0.005 = 0.01Kg/KgMSW (21)

Table-3. Oxygen Required per Kilogram of MSW

Constituent	Mass fraction	Oxygen required (Kg/Kg MSW)
Carbon (C)	0.355	0.947
Hydrogen (H)	0.051	0.408
Sulphur (S)	0.005	0.005
Oxygen (O)	0.239	- 0.239
Nitrogen (N)	0.024	___
Moisture	0.25	___
Ash	0.190	___
Total		1.121

O_2 required per Kilogram of MSW = 1.121Kg (22)

Air required per Kilogram of MSW = $\frac{1.121}{0.233}$ = 4.811Kg (23)

Where air is assumed to contain 23.3% O_2 by mass

ie. Stiochiometric air/fuel ratio = 4.811:1

For air supply which is 80% in excess (this has been derived from industrial experience according to (Chattopadhyay, 2006) which suggests that 80% of excess air is just enough to optimize the combustion of solid refuse in the mass-burning system.

Actual A/F ratio, m_{air} = 4.811 + $\left(\frac{80}{100} \times 4.811\right)$ = 8.660/1 (24)

Or alternatively, m_{air} can be found using Eq. (14)

Calculation of Calorific value of MSW

The first step in the processing of a waste is to determine its calorific content or heating value. This is a measure of the temperature and the oxygen requirements that the specific waste will be placed on the system (Frank *et al*., 2007). The calorific value of a fuel can be determined either from their chemical analysis or in the laboratory (Bujak, 2008). In the laboratory Bomb Calorimeter is used. The analysis of some sample of wastes from the Energy Centre, UNN using *Bomb Calorimeter* are shown in Table 4

Table-4. Calculation of Calorific value of the fuel using Bomb Calorimeter

Paper product	Wood waste	Plastics waste	Textile waste
Sample wt.,m,=1.060g	Sample wt.,m,=0.974g	Sample wt.,m,=1.023g	Sample wt.,m,=1.065g
Initial Temp. = $29.986^0 C$ Final Temp. = $31.009^0 C$ $\Delta T = 1.023^0 C$ $1.048^0 C$	Initial Temp. = $29.933^0 C$ Final Temp. = $30.981^0 C$ $\Delta T = 1.048^0 C$	Initial Temp. = $28.743^0 C$ Final Temp. = $30.457^0 C$ $\Delta T = 1.714^0 C$	Initial Temp. = $29.015^0 C$ Final Temp. = $30.695^0 C$ $\Delta T = 1.68^0 C$
Unburnt = 2.5+3.0=5.5	Unburnt = 1.3+2.2=3.5	Unburnt = 1.6+2.7=4.3	Unburnt = 2.5+0.8=3.3
Burnt = 10 - 5.5 = 4.5	Burnt = 10 - 3.5 = 6.5	Burnt = 10 - 4.3 = 5.7	Burnt = 10 - 3.3 = 6.7
$\Phi = 4.5 * 2.3 = 10.35$	$\Phi = 6.5 * 2.3 = 14.95$	$\Phi = 5.7 * 2.3 = 13.11$	$\Phi = 6.7 * 2.3 = 15.41$
$V = 2.3$	$V = 2.5$	$V = 3.9$	$V = 3.8$
$E = 13039.308$	$E = 13039.308$	$E = 13039.308$	$E = 13039.308$
$CV_p = (E\Delta T - \Phi - V)/m$	$CV_w = (E\Delta T - \Phi - V)/m$	$CV_p = (E\Delta T - \Phi - V)/m$	$CV_p = (E\Delta T - \Phi - V)/m$
$CV_P = 12572.22 J/g$	$CV_w = 14012.05 J/g$	$CV_P = 21833.26 J/g$	$CV_P = 20551.01 J/g$

= 12572.22KJ/kg	= 14012.05KJ/kg	= 21833.26KJ/kg	= 20551.01KJ/kg

(**Source;** National Centre for Energy Research & Development (NCERD), UNN.)

For chemical analysis, using *Dulong's formula,* percentage by mass was considered and heat of combustion of Carbon, Oxygen and Hydrogen determined as shown in Table 5

Table-5. Heat of combustion for C, S and H

Combustion	Heat of Combustion
$C+O_2 \rightarrow CO_2$	8075kcal/kg
$S + O_2 \rightarrow SO_2$	2220kcal/kg
$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	34500kcal/kg

(Source: P.Chattopadhyay, 2006**)**

Dulong suggested a formula for the calculation of the calorific of the fuel from their chemical composition as

$CV_{msw} = 8075(K_C) + 2220(K_S) + 34500(K_H - K_O/8)$ (25)

where K_C, K_S, K_H and K_O stand for percentage by mass of Carbon, Sulphur, Hydrogen and Oxygen respectively. Substituting the values of K_C, K_S, K_H and K_O from Table 2 will give,

$CV_{msw} = 8075(0.355) + 2220(0.005) + 34500(0.051\text{-}0.239/8)$

$CV_{msw} =$ 3,606.5Kcal/kg (26)

$CV_{msw} =$ 15,101 KJ/kg - - - - - - - - - (1cal = 4.187J)

Figures 2,3 & 4 show the views of the municipal waste steam boiler

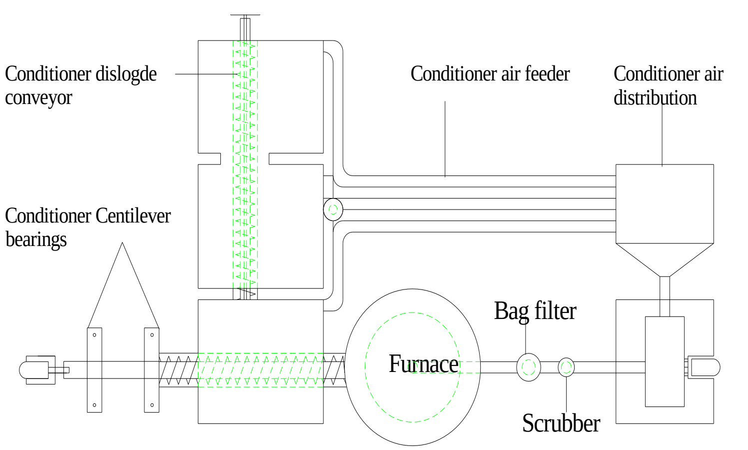

Figure 1 TOP VIEW OF MSW STEAM BOILER

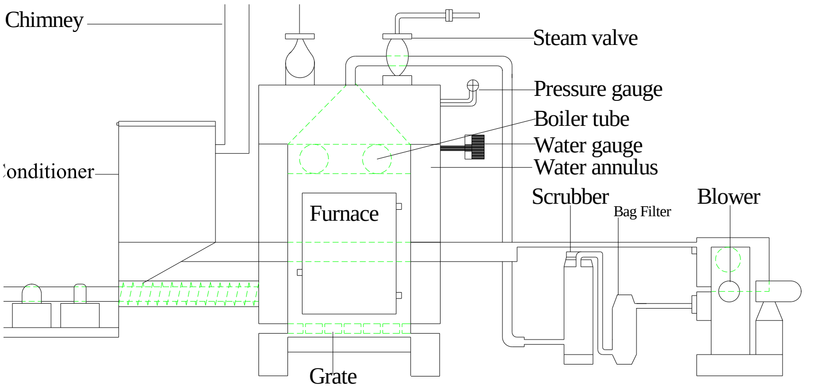

Figure 2 FRONT VIEW OF MSW STEAM BOILER

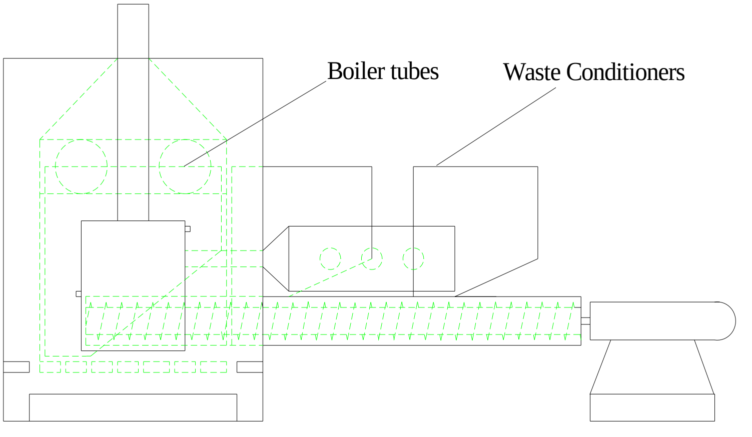

Figure 3 SIDE VIEW OF MSW STEAM BOILER

BOILER CALCULATIONS

Maximum Temperature of the Furnace

To obtain the maximum temperature attained in the furnace, the analysis of heat balance is necessary. This is calculated by the following equation (Frank *et al.*, 2007)**:**

Fig-4: Heat balance in the Furnace

$$Q_f = Q_{fg} + Q_s + Q_{uf} \quad (27)$$

Where, Q_f is the heat liberated in the furnace; Q_{fg} is the heat of the flue gas; Q_s is the heat used in producing steam and Q_{uf} is the heat lost due to unburnt fuel

$$Q_f = m_{msw} CV_{msw} \tag{28}$$

Where, m_{msw} and CV_{msw} are the mass of the fuel and the calorific value of the waste respectively

$$Q_{fg} = m_{fg} CP_{fg} (T_{fg} - T_o) \tag{29}$$

Where, m_{fg} is the mass of the flue gas; CP_{fg} is the specific heat capacity of flue gas; T_{fg} is the maximum temperature attained in the furnace and T_o is the boiler reference temperature.

$$Q_s = m_{st}(h_2 - h_1) \tag{30}$$

Where, m_s is the mass of the steam, h_2 and h_1 are respectively specific enthalpy of steam, at 10bar and specific enthalpy of feed water, at $25^0 C$

$$Q_{uf} = m_{uf} CV_{msw} \tag{31}$$

Where m_{uf} is the mass of unburnt fuel. Substituting (29)-(32) in (28), will yield

$$m_{msw} CV_{msw} = m_{fg} CP_{fg} (T_{fg} - T_o) + m_s (h_2 - h_1) + m_{uf} CV_{msw}$$

Hence

$$T_{fg} = \frac{m_{msw} CV_{msw}}{m_{fg} CP_{fg}} - \frac{m_{st} h_2 - h_1)}{m_f (m_{fg} CP_{fg})} - \frac{m_{uf} CV_{msw}}{m_{fg} CP_{fg}} + T_o \tag{32}$$

The heat flux lost through the external surfaces of the steam boiler to the environment is given by (Engineering, 2009)

$$Q_{ls} = 23 Q_{sb} (1.523 Q_{sb})^{-0.52} + \left(\frac{P}{5000}\right) P^{0.28} \tag{33}$$

Boiler Efficiency

The boiler thermal efficiency, η is calculated by the following equation (Bujak, 2008)**:**

$$\eta = \frac{\dot{Q}_{st}}{\dot{Q}_f} = \frac{\overset{*}{m}_{st}(h_2 - h_1)}{\overset{*}{m}_{msw} \times CV_{msw}} \times 100 = \frac{\text{Heat Supplied to the boiler}}{\text{Fuel energy}} \tag{34}$$

Equivalent Evaporation of Boiler

This is the amount of water evaporated at $100^0 C$, forming dry and saturated steam at $100^0 C$,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 the temperature (100 ° C). The value of this latent heat is taken as 2257 KJ/Kg. Thus, the equivalent evaporation, E of a boiler, from and at 100 ° C is [13]:

$$E = \frac{m_p(h_2 - h_1)}{2257} \quad (35)$$

Where $m_p = \frac{\overset{*}{m}_{st}}{\overset{*}{m}_{msw}}$ (36)

And the factor $\frac{(h_2 - h_1)}{2257}$ is known as factor of evaporation, and is usually denoted by F_e. Its value is always greater than unity for all boilers.

Boiler Horse Power (BHP)

It is very commonly used unit for measuring the capacity of a boiler. American Society of Mechanical Engineers (ASME) defines a unit boiler horse power as the boiler capacity to evaporate 15.653kg of BFW per hour and at 373K into dry, saturated steam or equivalent in heating effect.

$$BHP = \frac{E/hr}{15.653} \quad (37)$$

Furnace Calculations

Heat released rate per unit cross-sectional area of the furnace, q is given by

$$q = \frac{Q_{ft}}{A_{inc}} \quad (38)$$

Allowable heat released rate of the furnace, q_v

$$q_v = \frac{Q_{ft}}{V_{inc}} \quad (39)$$

RESULTS AND DISCUSSION

The Engineering Equation Solver (EES), developed at University of Wisconsin was used to obtain the solution of the equations.

Parameters for Solution of the Municipal Solid Waste-Boiler Design Equations

The results of the calculated parameters for municipal solid waste design equations from the previous section are shown in table 6

Table-6. Parameters for solution of the municipal solid waste-boiler design equations

S/N	Symbols	Calculated data	S/N	Symbols	Calculated data
1	A_c [m^2]	0.1971	31	m_{uf} [kg]	0.326
2	A_{cyl} [m^2]	0.4058	32	O_2 [%]	80
3	A_{inc} [m^2]	0.9553	33	P[N/m^2]	10^6
4	A_{tubes} [m^2]	0.01623	34	Q_{bw}[kJ]	134.6
5	BHP[kW]	0.2587	35	$\dot{Q}_f$ [KW]	2098
6	CP_{fg} [kJ/kg]	1.047	36	$\dot{Q}_{fg}$ [m^3/s]	2.841
7	CV_{msw} [KJ/kg]	15101	37	Q_f [kJ]	10178
8	D_c[m]	0.5529	38	Q_{fg} [kJ]	5235
9	D_{inc}[m]	0.7188	39	Q_{ls}[kJ]	9578
10	D_{oc}[m]	0.8343	40	Q_r[kJ]	6504
11	D_{tubes}[m]	0.07188	41	Q_s[kJ]	1269
12	E [kg/kg]	4.049	42	Q_{uf} [kJ]	1900
13	eff.[%]	60.52	43	ℓ_{fg} [kg/m^3]	0.4723
14	H[m]	7.02	44	r_1[m]	0.005643
15	H_1 [kJ/kg]	763	45	r_c [m]	0.05634
16	H_2[kJ/kg]	2778	46	S_t [N/m^2]	1.360×10^8
17	h_{fg} [m]	10.59	47	t [m]	0.005947
18	H_{inc} [m]	7.014	48	T_a [K]	298
19	h_o [m]	0.7099	49	T_o [K]	298
20	H_{tubes} [m]	0.7188	50	T_{fg} [K]	833.7
21	h_w [mm]	5	51	T_{mit} [m]	0.0507
22	h_{wmax} [m]	4.158	52	τ_r [s]	1.002
23	K [W/mK]	0.04	53	T_w [m^3]	550
24	m_{air} [kg]	8.66	54	V_{fgc} [m^3]	14.41
25	$\dot{m}_a [kg/s]$	1.203	55	V_{inc} [m^3]	2.835
26	$\dot{m}_{fg} [kg/s]$	1.342	56	V_T [m^3]	7
27	$\dot{m}_{msw} [kg/s]$	0.1389	57	V_{water} [m^3]	1
28	$\dot{m}_{st} [kg/s]$	0.63	58	q[kW/m^2]	2264
29	m_f [kg]	0.674	59	$\dot{Q}_{st}$ [kW]	1269
30	m_{fg} [kg]	9.334	60	q_v[KW/m^3]	739.9
			61	Ψ[KJ/Kg]	209.2

Influence of Moisture Content

Table-7. Results for variation of flue gas temperature in terms of column of calorific value of the fuel for different value of moisture content.

T_{fg} (K)	moisture	CV_{MSW} (KJ/Kg)	T_{fg} (K)	moisture	CV_{MSW} (KJ/Kg)	T_{fg} (K)	moisture	CV_{MSW} (KJ/Kg)
895.5	0.05	800	833.6	0.09	800	771.2	0.13	800
970.4	0.05	900	900.6	0.09	900	830.6	013	900
1045.0	0.05	1000	968.0	0.09	1000	890.0	0.13	1000
1120.0	0.05	1100	1035.0	0.09	1100	949.4	0.13	1100
1195.0	0.05	1200	1102.0	0.09	1200	1009.0	0.13	1200
1270.0	0.05	1300	1170.0	0.09	1300	1068.0	0.13	1300
1345.0	0.05	1400	1237.0	0.09	1400	1128.0	0.13	1400
1420.0	0.05	1500	1304.0	0.09	1500	1187.0	0.13	1500
1495.0	0.05	1600	1371.0	0.09	1600	1246.0	0.13	1600
1570.0	0.05	1700	1438.0	0.09	1700	1306.0	0.13	1700

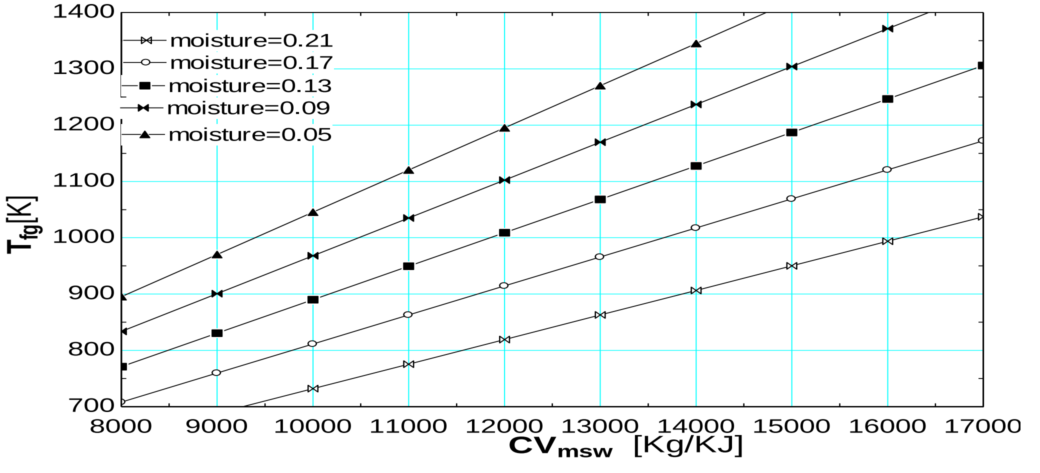

Figure-5. Variation of flue gas temperature in terms of column of calorific value of the fuel for different value of moisture content

Wastes with different moisture contents have different drying characteristics. Those with higher moisture content require a longer drying time and much more heat energy, causing a lower temperature in the furnace; and vice versa. If the moisture content is too high, the furnace temperature will be too low for combustion, such that auxiliary fuel is needed to raise the furnace temperature and to ensure normal combustion. In order to evaluate the effect of moisture content on the combustion process, numerical simulation and analysis were made with ten different values of moisture content .The results of the analysis show that those wastes with a lower moisture content give rise to higher furnace temperatures and larger high-temperature zones during combustion, because the wastes with lower moisture contents have higher heating values and are more combustibles, being easier and faster to burn. Hence, to increase the efficiency of the boiler, refuse conditioner was used in this work to dry the wastes before they were conveyed to the furnace.

Influence of Excess Air

The temperature in the furnace is closely related to MSW/air ratio. In order to predict the influence of excess air on the combustion in furnace, simulations were performed for different values of excess air. Results show that with the increase of excess air, the temperature of the furnace tends to decrease. To ensure adequate heating and burnout of wastes, a relatively high temperature level in the furnace should be maintained with a corresponding O_2 content.

Analysis of Elements Responsible For Energy Losses

Table-8. Results for variation of heat lost through external wall with usable power of steam boiler at difference values of operating pressure.

P(bar)	Q_{ls}(kW)	Q_s(kW)	P(bar)	Q_{ls}(kW)	Q_s(kW)	P(bar)	Q_{ls}(kW)	Q_s(kW)
10	2.360	200	210	2.54	200	410	2.79	200
10	3.990	600	210	4.17	600	410	4.43	600
10	5.094	1000	210	5.28	1000	410	5.53	1000
10	5.990	1400	210	6.17	1400	410	6.42	1400
10	6.750	1800	210	6.94	1800	410	7.19	1800
10	7.440	2200	210	7.62	2200	410	7.87	2200
10	8.060	2600	210	8.24	2600	410	8.49	2600
10	8.630	3000	210	8.81	3000	410	9.07	3000
10	9.160	3400	210	9.35	3400	410	9.60	3400
10	9.670	3800	210	9.85	3800	410	10.10	3800

Fig.6 shows heat flux lost to the atmosphere through the external surface of the steam boiler as a function of its thermal power and operating pressure. As shown in the figure, heat flux losses through the external surface of the boiler to the atmosphere increase with a rise in thermal power and operating pressure of saturated steam. It should be noted here that the value of the heat flux loss is dependent on the heat exchange surface, the temperature difference between the saturated steam and the ambient temperature, and the coefficient of heat transmission. Currently, only steam pressure and thermal power were taken into account.

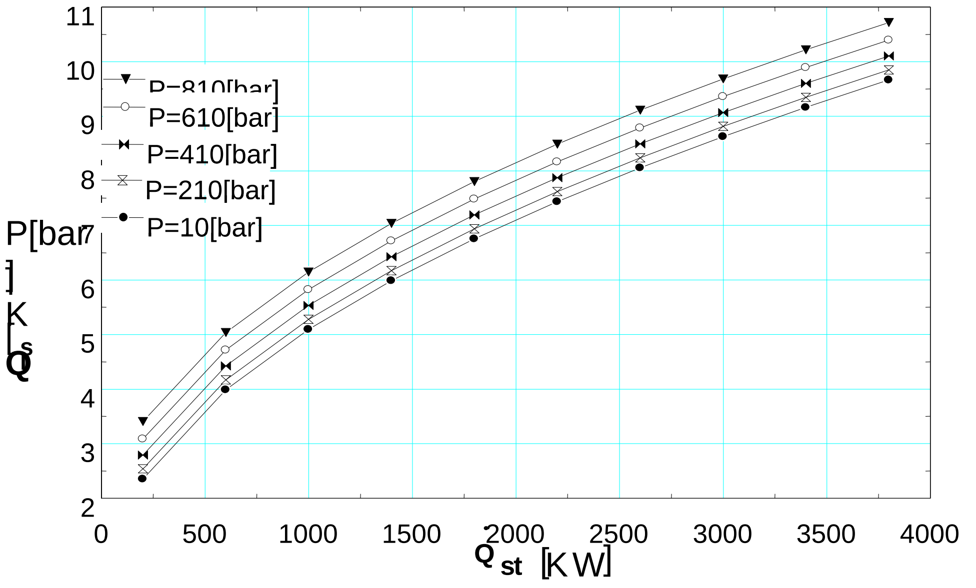

Figure-6. Variation of heat lost through external wall with usable power of steam boiler at difference value of operating pressure.

CONCLUSIONS

With the rapid development of national economy, the ever-accelerating urbanization and the continued improvement of living standard, the output of the solid waste, particularly Municipal solid waste is constantly increasing. This causes environmental pollution and potentially affects people's health, preventing the sustained development of cities and drawing public concern in all of the society. The continuously generated wastes take 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 In this work, calculation of calorific value of municipal waste has been carried out from the elemental composition of the waste using Dulong's formula. The result of 15,101 KJ/kg obtained agrees with type 1 waste, (Engineering, 2009) that contains 25 percent moisture contents from waste classifications. With this heating value, maximum temperature of the flue gas of 833.7K was calculated from the heat balance equation in the furnace.

Thermal analysis of the municipal solid waste boiler done with the operational conditions taken into account, showed that the municipal solid waste with higher moisture content has a lower heat value, corresponding to a lower temperature in the furnace and a lower O_2 consumption during combustion, resulting in a higher O_2 content at the outlet. Hence, for an efficient use of municipal solid waste as a fuel for generation of steam in boiler, waste with lower moisture content and adequate excess air supply should be used. In practical operation, the air supply rate and the distribution of the primary air along the grate should be duly adapted for the specific conditions of the wastes. An appropriate excess air ratio can effectively ensure the burnout of combustibles in the furnace, suppressing the formation and the emission of pollutants.

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Appendix: (EES Formulation of the MSW Steam Boiler Design Equations)

```
    "Physical Properties"
m_dot_msw=0.1389;CP_fg=1.047;
T_boiler=298;T_a=298;h_w=5;V_T=7;V_water=1;T_w=550;k=0.04;S_t=136*10^6[N/m^2];p=10
*10^5;{p=10}
CV_msw=15101
;h_2=2778;h_1=763;{N_2=0.024};Ash=0.076;moisture=0.25;o_2=80;m_dot_st=0.63;m_p=0.010;
K_st=16;m_steo=4.811;a_cp=1;K_C=0.355;K_H=0.051;K_O=0.239;K_S=0.05;K_N=0.024;K_M
=0.25;Z=0.80;T_0=298
"Sizing of the Chimney"
h_w=353*H*(1/T_a-(m_air+1)/m_air*(1/T_fg))
h_fg=H*(m_air/(m_air+1)*T_fg/T_a-1)
h_wmax=(353*H)/(2*T_a)
D_c=sqrt((4*m_dot_fg)/(4.43*sqrt(h_fg*pi*rho_fg)))
m_dot_fg=m_dot_msw+m_dot_a
m_dot_a=m_dot_msw*m_air
```

```
rho_fg=(353/T_fg)*(m_air+1)/m_air
m_dot_fg=Q_dot_fg*rho_fg
Q_dot_fg=V_fgc*A_c
V_fgc=sqrt(2*9.81*h_fg)
"Sizing of the Incinerator"
D_inc=sqrt((4*Q_dot_fg)/(pi*V_T))
H_inc=V_T*T_r
A_inc=A_cyl+A_tubes+A_strs+A_srec
A_cyl=(pi*D_inc^2)/4
V_inc=Q_dot_fg/T_r
D_tubes=1/10*D_inc
H_tubes=D_inc
A_tubes=4*(pi*D_tubes^2)/4
A_strs=2*((H_inc/10)*(2*D_inc/5))
A_srec=(2*pi*(2/5*D_inc)^2)/4
t=(p*D_inc)/(2*S_t)+0.003
V_water=(A_tubes*H_tubes)+(pi*D_oc^2/4-pi*D_inc^2/4)*H_inc
V_inc=((pi*D_inc^2/4)*H_inc)-(A_tubes*H_tubes)
 "Insulation"
r_c=k/h_o
h_o=0.29*((T_w-T_a)/H_inc)^0.25
r_1=t
t_mit=r_c-r_1
Q_bw=(2*pi*H_inc*(T_w-T_a))/((ln(r_c/r_1)/k)+(1/(h_o*r_c)))
"material balance analysis"
eff=((m_dot_st*(h_2-h_1)/(m_dot_msw* CV_msw))*100)
Q_f=m_f*CV_msw
Q_fg=m_fg*CP_fg*(T_fg-T_boiler)
Q_st=m_p*(h_2-h_1)
Q_uf=m_uf*CV_msw
Q_dot_f=m_dot_msw*CV_msw
BHP=E/15.653
q=Q_dot_f/A_inc
q_v=Q_dot_f/V_inc
Q_dot_st=m_dot_st*(h_2-h_1)
m_f=1-(Ash+moisture)
m_fg=m_f+m_air
m_air=4.811+(o_2/100*4.811)
m_uf=1-m_f
Q_f=Q_fg+Q_st+Q_uf
```

```
Q_ls=((23*Q_dot_st*(1.523*Q_dot_st)^(-0.52))/(100))+(p/5000)*p^0.28
Q_r=(5.67*10^(-8)*A_inc*0.73*(T_fg^4-T_fw^4))
E=(m_dot_st*(h_2-h_1)/(m_dot_msw* 2257))
D_out=(2*t)+D_inc
A_out=(2*pi*D_out)/4
A_con=A_out-A_inc
Q_st=(K_st*A_con*(T_fg-T_out))/t
Q_r=Q_dot_st+Q_fg
CP_fgas=(C_pc)/(a_ct+b_N+c_H+d_s)*(m_steo/m_fg)+f_A
a_ct=a_m/a_cp
a_m=(3.667*K_C)/(m_steo)
b_N=b_m/b_cp
b_cp=0.9094+1.69*10^(-4)*T_fg-(11135/T_fg^(2))
b_m=(0.767*(2.9978*K_H-0.3747*K_O+0.3747*K_S+K_C)*(11.445)+K_N)/m_steo
c_H=c_m/c_cp
c_cp=0.5657-6.68*10^(-6)*T_fg-(10465/T_fg^2)
c_m=((9*K_H+K_M)/m_steo)
d_s=d_m/d_cp
d_cp=exp(2.679-(151.16/T_fg)-0.289*ln(T_fg))
d_m=2*K_S/m_steo
f_A=f_m*C_pA
C_pA=0.7124*1.00011^(T_fg)*T_fg^0.051
f_m=m_steo*(n_t-1)/m_fg
n_t=1+Z
C_pc=(0.1874)*1.000061^(T_fg)*T_fg^(0.2665)
Ex=CP_fgas*((T_fg-T_0)-T_0*(ln(T_fg/T_0)))
```