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Recovery of Energy from Municipal Waste Products: Thermo-Chemical Analytical Approach

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Abstract:
The indiscriminate dumping of waste is a major concern to the environment. This has been the practice of most rural societies in third world countries including Nigeria over the past years. Research has exposed its effects to the environment as hazardous and responsible for various sources of pollution which has caused several atmospheric catastrophes. Thus, the work presented in this paper is an analytical recovery of energy from municipal waste product, this is one route of curbing the incessant effects of waste in the society. This study was achieved by setting up an experimental test bed with the aid of an incinerator, a Peltier element, a multimeter and other devices for proper analysis. The results established from this study confirms recovery of energy from waste. It is proven that office waste such as papers (C_2H_6O) and plastic (C_2H_4) materials like water cans, polyethylene baggage, etc are capable of producing up to 20.56W and 9.29W of electrical energy respectively from the small samples of waste used in a practical analysis. Similarly, it attests that the heat generated as a result of the combustion process yields 47256.07kJ/kg and 6164.78kJ/kg for C_2H_4 and C_2H_6O respectively at the application of same quantity of air supplied to the combustion chamber. Also, it confirms that excess air supplied to the combustion unit increases molar composition from 14.29mol to 18.57mol, however reducing exhaust emission for both cases. Meanwhile, the air/fuel ratio by mass decreases from 14.8kg to 10.36kg and 9.0kg to 6.31kg for C_2H_4 and C_2H_6O respectively in terms of theoretical air supply which prompts the increase of exhaust products in the combustion process. Therefore, it is optimistic that the technique adopted in the study is viable.

Keywords: Air/Fuel Ratio, Combustion, Gravimetric Composition, Municipal Solid Waste, Paper, Plastic, Power.

I. INTRODUCTION

Over the last few decades one of the biggest global challenges is the struggle with the delivery of effective and sustainable waste management system together with good sanitation [1]. Municipal solid waste (MSW) also called trash or garbage, describes the collection and disposal of urban waste, including most of the produce from households, businesses and local authorities. MSW consists mainly of paper, food, wood, garden, cotton and leather waste, as well as some fossil fuel materials, such as plastics [2]. Consequently, these waste disposals generally comprise of depositing wastes in open or excavated landfills, accompanied by open burning to reduce waste volumes. Although, industrial hazardous wastes were co-disposed with municipal garbage and refuse in landfills; however, the improper management of MSW has severe environmental challenges. Thus, historical environmental problems associated with landfills include ground water contamination water sources, emissions of toxic fumes, greenhouse gases (GHG) that contribute to global warming, land contamination, increase in pest and disease vector population like rodents, flies, mosquitoes, etc [3]-[5]. Similarly, in developing countries, most of the solid waste generated is in landfills and open air sites causing serious risks to public health and the environment [6].

Beyond the environmental impacts of disposal, economic growth and increase in prosperity have been correlated with increase in material consumption. This has led to the increase in waste to land filling without meeting the sustainable development and economic well-being of the people [7]. Hence, this has propelled several researches to track alternative and efficient methods of the MSW usage. However, with the increase in population, accelerated urbanization, and economic development; living standard is gradually improving. Thus the growing capacity for MSW reflects these changes which is currently being achieved using landfills [2]. Although, diverting waste from landfill is one of the basic priorities on improving the use of resources and reducing the environmental impacts of waste management [8]; hence, the adoption of waste-to-energy (WTE) technology is crucial to effective sustainable MSW management [2].

Waste management and disposal is a pressing issue challenging the global community today [9]. The unavailability of suitable facilities to treat and dispose MSW generated daily in the past has subsequently raised degradation of the environment over time [10]. Therefore, the objective of integrated waste management is to deal with society’s waste in an environmentally and economically sustainable way [11]. Thus, the ineffective management of MSW can be traced to barriers like partial or no segregation of waste that increase the landfill load, lack of indigenous technology, inappropriate transportation of waste, lack of secondary storage space, improper disposal techniques, and scarce technical and managerial inputs for proper handling and treatment of waste [12]. Successful waste management requires the participation of citizens, government and private entrepreneurs [9]. Moreover, different waste management practices are laced to MSW, such as material recovery and recycling, energy recovery, and ultimately land filling [6]. Also according to a reviewed study, MSW management encompasses the functions of collection, transfer resource recovery, recycling, and treatment [13]. Therefore, as established in findings, the technologies to manage and further reduce GHG emissions include landfilling with biogas recovery, composting of selected waste fractions, anaerobic digestion and thermal processes including incineration, gasification and pyrolysis [12].

Conversely, several researches has been conducted using the above prescribed methods to improve the WTE generation. In view of research contribution on combustion of MSW for energy production using gasification, results attest that it has a higher flexibility to accommodate different waste composition, heating values, lower pollutant emissions, higher temperatures and efficient power generation [14,15]. Similarly, according to a scholarly study on combustion using incinerator has been revealed that MSW incineration gives high return on energy while staying low on the energy consumed. It also enhances improvement on the environment by reducing the GHG emission and amount of waste that must be land filled [16]. Hence, this work was meant to evaluate energy and power generated from MSW incinerator vis–a-viz the analysis of voltage and current produced from different types of waste products as a result of combustion process in the incinerator.

II. Materials and Method

The feasibility of the study depends on the materials used in carrying out the research. Therefore, in order to recover useable energy from municipal waste products analytically; an incinerator designed and fabricated in the mechanical engineering workshop of Niger Delta University, Wilberforce Island, Bayelsa State was used to carry out the experimental study. Other materials used are peltier element which was used in converting heat energy to electrical energy and multimeter for measurement of voltage and current. These are shown in figures 1 - 3.

Figure 1: Pictorial View of an Incinerator

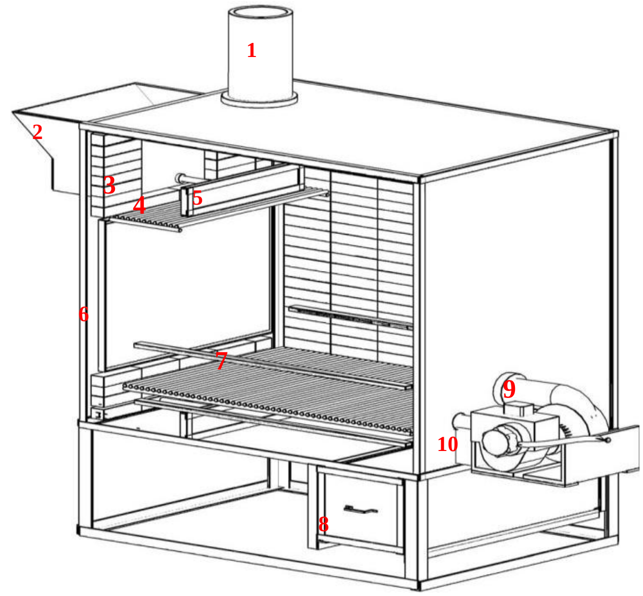

Figure 2: Isometric view of the Incinerator

1. Chimney, 2. Hopper, 3. Refractory bricks, 4. Drying grate
5. Feed ram, 6. Combustion air piping, 7. Combustion gate
8. Ash tray, 9. Blower, 10. Burner

Figure 3: Peltier Element

III. Experimental Setup

A radiator was connected at the exit of the chimmey in order to emit heat with series connection to the peltier element placed on top of the radiator. This is to enable heat conduction between the two materials. However, the peltier element with electrical terminals was connected to a multimeter for appropriate parametric measurement to justify findings. Meanwhile, the incinerator was charged with different samples of MSW of same weight at different time interval while combustion process was commenced. In order to determine the effectiveness of the combustion process of each MSW introduced into the incinerator, various analysis of stoichiometric chemical equations was considered for each waste sample representing the fuel in the process. This also will further give clear analysis of heat generated from the combustion process.

IV. Stoichiometric Analysis of Municipal Solid Waste

Organic waste samples of the same weight were collected from the university environs for the experiment. Thus, the sampled waste for this purpose were office stationaries such as papers and littered plastic and rubber waste such as sachet waterproof and plastic bottles, plastic bags, condemn lamination films, spiral binding waste materials, etc. Plastic and rubber are commonly known as polyethylene (ethene); the alkene's family of hydrocarbons with pi and sigma double bonds. It has a general chemical formula of $(C_2H_4)_n$, where n represents the number or position of the compound in the alkene's family. The usefulness of polyethylene is limited by its thermal properties at the range of 80 - 180℃ [17]. It is a nonpolar saturated with high molecular weight. Its chemical behavior is similar to paraffin. Hence, it burns slowly with a blue flame having a yellow tip and gives off an odour similar to candle wax. Plastic is a material consisting of wide range synthetic or semi-synthetic organics that are malleable and can be moulded into solid objects of diverse shapes [17].

Conversely, the historical background of paper is traceable to its raw agro-product which is wood. It is the main constituent of cell walls of plants, and is represented by the chemical formula $(C_6H_{10}O_5)_n$, where n symbolizes the number of cellulose units. Hence, the stiochiometric equations for plastic polyethylene and paper MSW are presented in table 1 for this study while tables 2 and 3 are their thermodynamic analysis respectively.

Table 1: Stoichiometric Chemical Combustion Equations

MSW	Air Supply		Equations
Polyethene Plastic (C_2H_4)	Theoretical Air	100%	$C_2H_4 + 3O_2 + 3(79/21)N_2 \rightarrow 2CO_2 + 2H_2O + 3(79/21)N_2$
		90%	$C_2H_4 + 2.7O_2 + 2.7(79/21)N_2 \rightarrow 1.4CO_2 + 0.6CO + 2H_2O + 2.7(79/21)N_2$
		80%	$C_2H_4 + 2.4O_2 + 2.4(79/21)N_2 \rightarrow 0.8CO_2 + 1.2CO + 2H_2O + 2.4(79/21)N_2$
		70%	$C_2H_4 + 2.1O_2 + 2.1(79/21)N_2 \rightarrow 0.2CO_2 + 1.8CO + 2H_2O + 2.1(79/21)N_2$
	Excess Air	110%	$C_2H_4 + 3.3O_2 + 3.3(79/21)N_2 \rightarrow 2CO_2 + 2H_2O + 0.3O_2 + 3.3(79/21)N_2$
		120%	$C_2H_4 + 3.6O_2 + 3.6(79/21)N_2 \rightarrow 2CO_2 + 2H_2O + 0.6O_2 + 3.6(79/21)N_2$
		130%	$C_2H_4 + 3.9O_2 + 3.9(79/21)N_2 \rightarrow 2CO_2 + 2H_2O + 0.9O_2 + 3.9(79/21)N_2$
Paper (C_2H_6O)	Theoretical Air	100%	$C_2H_6O + 3O_2 + 3(79/21)N_2 \rightarrow 2CO_2 + 3H_2O + 3(79/21)N_2$
		90%	$C_2H_6O + 2.7O_2 + 2.7(79/21)N_2 \rightarrow 1.4CO_2 + 0.6CO + 3H_2O + 2.7(79/21)N_2$
		80%	$C_2H_6O + 2.4O_2 + 2.4(79/21)N_2 \rightarrow 0.8CO_2 + 1.2CO + 3H_2O + 2.4(79/21)N_2$
		70%	$C_2H_6O + 2.1O_2 + 2.1(79/21)N_2 \rightarrow 0.2CO_2 + 1.8CO + 3H_2O + 2.1(79/21)N_2$
	Excess Air	110%	$C_2H_6O + 3.3O_2 + 3.3(79/21)N_2 \rightarrow 2CO_2 + 3H_2O + 0.3O_2 + 3.3(79/21)N_2$
		120%	$C_2H_6O + 3.6O_2 + 3.6(79/21)N_2 \rightarrow 2CO_2 + 3H_2O + 0.6O_2 + 3.6(79/21)N_2$
		130%	$C_2H_6O + 3.9O_2 + 3.9(79/21)N_2 \rightarrow 2CO_2 + 3H_2O + 0.9O_2 + 3.9(79/21)N_2$

Table 2: Thermodynamic Analysis for C_2H_4

Theoretical Air (%)	Air/Fuel Ratio		Volumetric Composition			Gravimetric Composition				Internal Energy of Combustion; ΔUo (KJ/Kg)
	Mole	Mass	% Production of			% Production of				
	(mol)	(kg)	CO_2	CO	N_2	CO_2	CO	H_2O	N_2	
100	14.29	14.80	15.05	-	84.95	19.97	-	8.21	71.82	-47256.07
90	12.86	13.32	11.51	4.93	83.55	15.40	4.21	9.05	71.30	-47282.62
80	11.43	11.84	7.25	10.88	81.87	9.86	9.39	10.09	70.66	-47309.16
70	10.00	10.36	2.02	18.18	79.80	2.74	15.93	11.42	69.91	-47335.71
Excess Air	Mole	Mass	% Production of			%Production of				ΔUo
(%)	(mol)	(kg)	CO_2	CO	N_2	CO_2	CO	H_2O	N_2	(KJ/Kg)
100	14.29	14.80	15.05	-	84.95	19.97	-	8.21	71.82	-47256.07
110	15.71	16.27	13.60	2.04	84.36	18.28	1.98	7.51	72.36	-47256.07
120	17.14	17.75	12.39	3.72	83.89	16.83	3.54	6.91	72.56	-47256.07
130	18.57	19.23	11.38	5.12	83.49	15.60	5.12	6.41	72.88	-47256.07

Table 3: Thermodynamic Analysis for C_2H_6O

Theoretical Air (%)	Air/Fuel Ratio		Volumetric Composition			Gravimetric Composition				Internal Energy of Combustion ΔUo (KJ/Kg)
	Mole	Mass	% Production of			% Production of				
	(mol)	(kg)	CO_2	CO	N_2	CO_2	CO	H_2O	N_2	
100	14.28	9.00	15.06	-	84.94	19.20	-	11.76	69.04	-6164.78
90	12.86	8.11	11.11	4.93	83.55	14.79	4.08	12.91	68.21	-6180.93
80	11.43	7.21	7.25	10.88	81.87	9.43	8.94	14.33	67.30	-6197.09
70	10.00	6.31	2.02	18.18	79.80	2.62	15.08	16.10	66.20	-6213.25
Excess Air	Mole	Mass	% Production of			% Production of				ΔUo
(%)	(mol)	(kg)	CO_2	CO	N_2	CO_2	CO	H_2O	N_2	(KJ/Kg)
100	14.28	9.00	15.06	-	84.94	19.20	-	11.76	69.04	-6164.78
110	15.71	9.90	13.59	2.04	84.36	17.60	1.94	10.78	69.68	-6164.78
120	17.14	10.81	12.39	3.72	83.89	16.27	3.58	9.97	70.19	-6164.78
130	18.57	11.71	11.38	5.12	83.50	15.11	4.98	9.26	70.65	-6164.78

Table 4 presents the analysis of the result of power generation from the combustion process of the MSW samples. This was obtained from the peltier element experimental setup with the aid of multimeter measuring the appropraite voltage and current respectively to estimate the power generated over a combustion duration of 30 minututes at an interval of 2 minutes. However, the graphical plots in figure 4 describes the power output from the combustion of both MSW products.

Table 4: Measurement of Output Power

Duration (min)	Paper MSW			Plastic Polyethene MSW		
	Current (A)	Voltage (V)	Power (W)	Current (A)	Voltage (V)	Power (W)
0	0	0	0	0	0	0
2	0	0	0	0	0	0
4	0.08	0.18	0.01	0	0	0
6	0.23	0.53	0.12	0.01	0.02	0.00
8	0.89	2.05	1.82	0.06	0.14	0.01
10	1.31	3.01	3.95	0.10	0.23	0.02
12	1.49	3.43	5.11	0.15	0.35	0.05
14	1.79	4.12	7.37	0.25	0.58	0.14
16	1.99	4.58	9.11	0.45	1.04	0.47
18	2.21	5.08	11.23	0.91	2.09	1.90
20	2.42	5.57	13.47	1.31	3.10	4.06
22	2.51	5.77	14.49	1.71	3.93	6.73
24	2.99	6.88	20.56	1.93	4.44	8.57
26	2.71	6.23	16.89	2.01	4.62	9.29
28	1.01	2.32	2.35	2.01	4.62	9.29
30	0.09	0.21	0.02	1.01	2.32	2.35

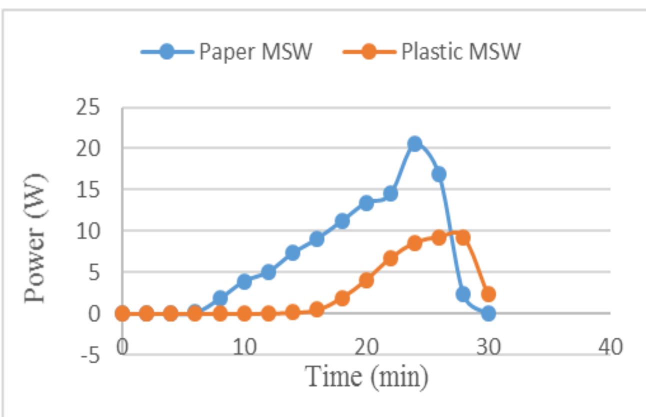

Figure 4: Graph Plot of Power from MSW

In order to evaluate the heat evolved in the combustion of the MSW, a non-flow energy equation for combustion at constant volume (shown in equation 1) was considered which illustrated the process in figure 5. The internal energy change is independent of the path between the two states and depends only on the initial and final values given by the quantity, Q. Thus, Q is considered as the heat transfer and also the internal energy of combustion or constant volume heat of combustion at T_o, which is shown in equations 2 and 3 used in the analysis.

$$Q = (U_2 - U_1) + W \qquad 1$$

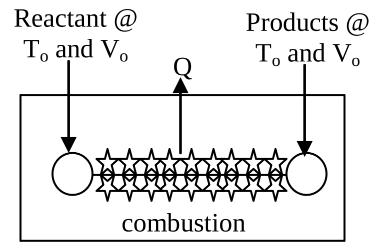

Figure 5: Combustion Process [18]

$$\Delta Uo = (UP_o - UR_o) + W \qquad 2$$

Hence, U = h – Pv at a standard state of 25° at 1atm.

$$\Delta Ho = \Delta Uo + R_o T_o (n_P - n_R) \qquad 3$$

Where ΔHo = Enthalpy of combustion @ T_o
To = Reference temperature (25°)

Meanwhile, assumed values of -1323170KJ/mol and -281102KJ/mol for ΔHo are used for C_2H_4 and C_2H_6O respectively from reviewed literature, while; value for universal gas constant, R_o = 8.3144KJ/Kmol and reference temperature at standard state of 25° (T_o = 298K) at 1atm are used as well for the calculations [18, 19].

V. DISCUSSION OF RESULTS

Results from the study indicates close range of theoretical and excess air/fuel ratio of the waste samples both in molecular and by mass bases. It is observed that reduction in theoretical air supply for the combustion process of the MSW reduces the molar composition by 14.29mol – 10.0mol in both cases whereas, increase in air supply to the combustion process from 100% - 130% excess air increases the molar composition from 14.29mol – 18.57mol. Similarly, air/fuel ratio by mass decreases from 14.8kg – 10.36kg and 9.0kg – 6.31kg for C_2H_4 and C_2H_6O respectively in terms of theoretical air supply. However, reverse is the case in terms of addition of excess air. This records an increment of 4.43kg and 2.71kg for C_2H_4 and C_2H_6O respectively.

Obviously, the resultant effect of the reduction of the air/fuel ratio gives rise to an increase in the exhaust products from the combustion process. This is confirmed as the summation of CO_2 and CO generate high volumetric composition value of 69.83% in terms of theoretical air against excess air of 63.31% for C_2H_4 and C_2H_6O respestively. Perhaps, this justify the reason for the addition of excess air in a combustion process burn off all the fuels and yeild less or no exhaust products capable of depleting the ozone layer. Hence, supply of more air enhance burning and reduces emission to the environment.

Heat evaluation as observed from the analysis attests to constant generation of internal energy of combustion of -47256.07kJ/kg for the plastic MSW and -6164.78kJ/kg for paper MSW when there is an excess supply of air. However, the heat reduces as the theoretical air supply decreases in percentage for both cases. Thus, from analysis more heat is generated from the combustion of C_2H_6O than C_2H_4. Finally, this confirms the generation of more useful energy of 20.56W from the same MSW against 9.29W of the plastic wastes products as shown in figure 4.

VI. CONCLUSION

The study of energy recovery from municipal waste products using the experimental setup with an incinerator was feasible and justifiable due to the following reasonable results obtained.

- Domestic solid waste such as papers, plastic bottle cans, polyethylene baggage and bags, Sachet waterproof and water bottles are effective sources for sustainable energy.
- Results attests to the fact that every little amount of heat generated from a MSW incinerator is capable of producing corresponding amount of power.
- The energy produced is a function of heat and depends on the amount of air supplied to the combustion chamber.
- It also confirms that inadequate supply of air will increase incomplete combustion of MSW and thus will intensify negative environmental impact such as emissions capable of depleting the stratosphere.

Therefore, the study of harnessing and converting latent energy from municipal waste products to useful, reliable and sustainable energy should be encouraged. This will reduce the over dependence on conventional energy sources and thus, the environment will be clean, friendly and serene for living.

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