# Gross Calorific Value of Combustible Solid Waste in a Mass Burn Incineration Plant, Benin City, Nigeria

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**ABSTRACT:** Some solid waste incinerators burn waste that does not possess enough calorific value that justifies the installation of an energy recovery facility, this implies that a substantial amount of energy would be provided by an auxiliary burner. Hence, the presentation of this paper was to evaluate the feasibility of setting up a mass burn incinerator with energy recovery facility using the gross calorific value (GCV) of waste generated in Benin City of Nigeria which is considered as case study. Solid waste samples (wood, leather rubber, plastic, paper, textile material etc.) were collected from Benin metropolis and their GCV were determined in a laboratory using an XRY-1A digital oxygen bomb calorimeter. The average calorific value of the waste samples calculated from the experiment was 20,198.89*kJ/kg*, this value is higher than the 7,000*kJ/kg* minimum average calorific value of solid waste required for setting up an incineration plant with energy recovery.

The design and operation of the plant (incinerator) meant for the processing of solid waste are highly related to the gross calorific value (GCV) of the solid waste materials (Ebru *et al*, 2009). Thus, determining the heating value of municipal solid waste is a key work to be performed in the efficient design and operation of a waste to energy conversion based technology. Benin Metropolis encompasses Benin City the capital City of the ancient Bini kingdom and it is made up of three local Government areas – Oredo, Egor and Ikpoba-Okha local government areas. The total Population in Benin metropolis is made up of about 1,085,676 persons (National Population Commission, 2006). As unveiled in a scholarly research finding, waste generation survey carried out in Benin metropolis shows 0.425kg of solid waste generated per person per day (*ppd*). It also shows that over 20% of recyclable solid waste is generated from domestic source of solid waste. Thus, the average percentage (%) component of household solid waste generated in the studied environs reveals 9% plastic/rubber, 4% paper, 1% unclassified combustible materials, 4% metal, 3% glass, 78% food waste and 1% ash (Igbinomwanhia et al., 2014). The first step in the processing of a waste is to determine its calorific content or heating value. The parameter that is necessary for the definition of the energetic content of the materials is the gross calorific value (*GCV*) or higher heating value (*HHV*) defined as the quantity of

heat generated by the complete combustion of a unit mass of sample at constant volume in an oxygen atmosphere assuming that both the water contained in the sample and that generated by the combined hydrogen, remain in liquid form (Carlos *et al*, 1991). The calorific value of a fuel can be determined either from their chemical analysis or in the laboratory experimentally by a bomb calorimeter. According to Obernberger (2006), the whole process of thermal utilization (fuel supply, combustion system, solid and gaseous emissions) of solid biofuels is influenced by the kind of solid biofuel used, its physical characteristics (e.g. particle size, bulk density, moisture content, calorific value) and its chemical composition. The GCV of different agroforestry species and bio-based industry residues was experimentally determined by Loannis (2016), the fuel samples used were from agricultural residues and wastes (rice husks, apricot kernels, olive pits, sunflower husks, cotton stems, etc.), energy crops and wetland herbs (cardoon, switchgrass, common reed, narrow-leaf cattail). The GCV of the different agroforestry species and residues ranges from 14.3 – 25.4 *MJ/kg*. The highest GCV was obtained by seeds and kernels due to higher unit mass and higher lipid content. Pinus sylvestris with moisture content 24.59% obtained the lowest GCV (13.973 *MJ/kg*). In a similar research work carried out by Gabriel (1983) is an experimental determination of the calorific

values of some Nigerian solid fuel materials such as rice husk, corn cob, corn grain, corn Stover, saw dust, wood shavings, palm kernel husk and coal. The results showed that GCV ranges from 19,642 KJ/kg to 13,643 KJ/kg for palm kernel husk and rice husk respectively which compared favourably with Nigeria's sub-bituminous coal with a GCV of 28,466 KJ/kg. Munoz (2004) determined the calorific values of coals using differential thermal analysis (DTA) technique in which eight Spanish coal samples of different origin and rank were studied. The calorific values obtained by DTA revealed a high level of correspondence to those obtained by ASTM (American Society of Testing and Materials) method and those calculated from a semi-empirical equation.

Ayhan (2004) carried out an experiment on pyrolysis of beech trunk bark to obtain bio-char and pyro-oil for the purpose of determining their calorific values. The experiments were designed to investigate the effects of both the heating rate and temperature of pyrolysis on pyro-oil and bio-char yields and their characteristics. Therefore, the purpose of this research work was to determine the GCV of combustible solid waste in Benin metropolis in order to assess the feasibility of establishing an incineration plant with energy recovery facility.

## MATERIALS AND METHODS

Combustible solid waste samples were collected from Benin metropolis in Edo state, the South-South geopolitical region of Nigeria. The samples were dried and $1g$ of each was weighed and prepared for test.

*Calorimetric Test Procedure:* The determination of the GCV of a material involves carrying out an experiment using a XRY-1A digital oxygen bomb calorimeter. The calorimetric test was performed at the National Centre for Energy and Environment, Benin City. The sample for the experimental determination was weighed and placed in a combustion bomb and lowers inside a water bucket. The stirrer of the calorimeter was activated to make temperature of the water uniform at every part of the bucket. Readings were taken at an interval of 30 seconds over 5 minutes and recorded. Thereafter the firing button was activated to ignite the sample, upon combustion of the sample, heat is released and transferred through the wall of the combustion bomb and used to raise the temperature of the water inside the bucket. The temperature rise of the water was recorded after 30 seconds interval of time over 15 minutes and recorded.

*Calculation of GCV*: The gross calorific values (GCV) of the solid waste samples were calculated using the

formula in equation 1 and the results are presented in Table 3.

$$GCV = \frac{C\Delta T - (e_1 + e_2 + e_3)}{m} \qquad (1)$$

$GCV$ = Gross calorific value of sample; $C$ = Specific heat capacity of calorimeter; $m$ = Mass of sample; $\Delta T$ = Net corrected temperature rise; $\Delta T$ is calculated using equation 2

$$\Delta T = (T_c - T_a) - r_d \qquad (2)$$

$T_a$ = Temperature at time of firing; $T_c$ = Maximum temperature; $-r_d$ = Correction of heat loss (or gain) by radiation, $-r_d$ is calculated for heat loss or gain by radiation using equation 3 and 4 respectively;

$$-r_d = +r_1(b-a) + r_2(c-b) \text{ (for heat loss by water inside bucket)} \quad (3)$$

$$-r_d = -r_1(b-a) - r_2(c-b) \text{ (for heat gain by water inside bucket)} \quad (4)$$

Where: $a$ = Time of firing; $b$ = Time when temperature reaches 60% of the total rise, = Time corresponding to $T_a$ + 60% rise in temperature; $c$ = Time at which temperature is maximum; $r_1$ = Rate at which temperature was falling (of rising) during stirring, calculated using eqn. 5

$$= T_1 - T_{11} \text{ (i.e. temperature change within 5}min\text{)} \quad (5)$$

$r_2$ = Rate at which temperature was falling after time $c$, calculated using eqn.6

$$= T_{25} - T_{31} \text{ i.e. temperature change within 3}min\text{)} \quad (6)$$

$e_1$ = Correction of heat of formation of nitric acid

However, flushing the bomb with oxygen prior to firing, displaces all nitrogen, thereby eliminates nitric acid formation. Hence, $e_1 = 0$

$e_2$ = Correction of heat of formation of sulphuric acid, calculated from eqn.7
= % of sulfur in the sample $\times$ 57.54 $J$ $\times$ mass of sample  (7)
$e_3$ = Correction of heat of formation of fuse wire, calculated from eqn. 8
= Length of fuse wire consumed  $\times$ 9.66 $J$ (8)

## RESULTS AND DISCUSSION

The readings recorded from stirring of water inside the bucket is presented in Table 1. This experiment was carried out prior to the ignition of the waste sample in order to create an even temperature distribution in the water jacket. Table 1 reveals that the stirring of water in the bucket over a period of time (5 minutes) resulted in reduction of temperature and it eventually became stable at a point. This is because at the beginning of the stirring process there was temperature difference in various parts of the water inside the bucket, but as stirring continued over the passage of time the temperature of water became uniform in all the parts. The temperature profile in the water jacket after ignition of the waste samples is presented in Table 2. It can be observed from the readings recorded after firing the calorimeter that the temperature rise is rapid during the first 5 minutes and then it becomes slower as the temperature approaches a stable maximum after about 12 minute when the samples must have released all their energy (heat) content. This can be used to predict when to use an auxiliary burner to maintain the temperature inside the combustion chamber.The Calorific values of the individual waste samples were determined separately using equation1 and a complete compilation of the result is presented in Table 3. According to the results obtained from the experimental determination of GCV of the solid waste samples shown in Table 3, the highest calorific value was obtained for plastic (33,712 *kJ/ kg*), this is due to the high percentage of combustible elements (hydrogen and carbon) present in the constituent while that of white paper (14,085 *kJ/ kg*) is the lowest, these values agree with the results reported by Alter (1987) and Gidarakos *et al* (2006).

**Table 1:** Readings recorded from the stirring of water inside the bucket

| S/N | Time (*min*) | Wood T (ºC) | Leather T (ºC) | Rubber T (ºC) | Plastic T (ºC ) | W.Paper T (ºC ) | B.Paper T (ºC ) | Rubber T (ºC ) | PKF T (ºC ) | PKS T (ºC ) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0 | 29.398 | 28.793 | 27.226 | 27.819 | 29.216 | 29.208 | 28.237 | 29.144 | 29.350 |
| 2 | 0.5 | 29.398 | 28.776 | 27.230 | 27.817 | 29.213 | 29.206 | 28.235 | 29.142 | 29.348 |
| 3 | 1.0 | 29.399 | 28.766 | 27.233 | 27.816 | 29.208 | 29.207 | 28. 235 | 29.135 | 29.347 |
| 4 | 1.5 | 29.397 | 28.759 | 27.235 | 27.815 | 29.199 | 29.206 | 28. 235 | 29.128 | 29.344 |
| 5 | 2.0 | 29.396 | 28.753 | 27.236 | 27.814 | 29.197 | 29.203 | 28. 235 | 29.123 | 29.342 |
| 6 | 2.5 | 29.395 | 28.747 | 27.238 | 27.814 | 29.194 | 29.202 | 28.236 | 29.119 | 29.341 |
| 7 | 3.0 | 29.394 | 28.742 | 27.239 | 27.812 | 29.192 | 29.201 | 28.236 | 29.115 | 29.339 |
| 8 | 3.5 | 29.393 | 28.741 | 27.241 | 27.812 | 29.189 | 29.200 | 28. 235 | 29.111 | 29.338 |
| 9 | 4.0 | 29.391 | 28.741 | 27.242 | 27.811 | 29.187 | 29.199 | 28. 235 | 29.109 | 29.335 |
| 10 | 4.5 | 29.390 | 28.740 | 27.243 | 27.810 | 29.186 | 29.197 | 28. 235 | 29.106 | 29.332 |
| 11 | 5.0 | 29.390 | 28.740 | 27.243 | 27.810 | 29.186 | 29.197 | 28. 235 | 29.105 | 29.330 |

**Table 2:** Readings recorded for the combustion of 1.00*g* sample of the solid waste

| S/N | Time (*min*) | Wood T (ºC) | Leather T (ºC) | Rubber T (ºC) | Plastic T (ºC) | W.Paper T (ºC) | B.Paper T (ºC) | Textile T (ºC) | PKF T (ºC) | PKS T (ºC) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0 | 29.389 | 29.696 | 27.293 | 27.812 | 29.186 | 29.196 | 28.235 | 29.104 | 29.331 |
| 2 | 0.5 | 29.510 | 29.808 | 27.548 | 28.325 | 29.560 | 29.270 | 28.387 | 29.272 | 29.491 |
| 3 | 1.0 | 29.788 | 29.842 | 27.780 | 28.717 | 29.660 | 29.428 | 28.705 | 29.758 | 29.694 |
| 4 | 1.5 | 30.000 | 29.873 | 27.966 | 28.907 | 29.734 | 29.634 | 28.918 | 30.010 | 29.872 |
| 5 | 2.0 | 30.134 | 29.895 | 28.126 | 29.370 | 29.759 | 29.712 | 29.042 | 30.138 | 30.004 |
| 6 | 2.5 | 30.215 | 29.915 | 28.242 | 29.528 | 29.790 | 29.781 | 29.123 | 30.235 | 30.098 |
| 7 | 3.0 | 30.314 | 29.931 | 28.326 | 29.636 | 29.805 | 29.837 | 29.220 | 30.330 | 30.191 |
| 8 | 3.5 | 30.349 | 29.943 | 28.409 | 29.715 | 29.823 | 29.881 | 29.250 | 30.429 | 30.266 |
| 9 | 4.0 | 30.376 | 29.954 | 28.482 | 29.778 | 29.838 | 29.895 | 29.278 | 30.492 | 30.325 |
| 10 | 4.5 | 30.396 | 29.963 | 28.535 | 29.828 | 29.853 | 29.951 | 29.299 | 30.526 | 30.370 |
| 11 | 5.0 | 30.413 | 29.970 | 28.582 | 29.861 | 29.864 | 29.977 | 29.317 | 30.566 | 30.406 |
| 12 | 5.5 | 30.425 | 29.976 | 28.625 | 29.893 | 29.872 | 29.997 | 29.330 | 30.599 | 30.436 |
| 13 | 6.0 | 30.436 | 29.980 | 28.660 | 29.922 | 29.879 | 30.016 | 29.342 | 30.628 | 30.457 |
| 14 | 6.5 | 30.445 | 29.985 | 28.679 | 29.947 | 29.885 | 30.031 | 29.351 | 30.648 | 30.479 |
| 15 | 7.0 | 30.453 | 29.987 | 28.700 | 29.966 | 29.892 | 30.047 | 29.360 | 30.666 | 30.493 |
| 16 | 7.5 | 30.457 | 29.988 | 28.722 | 29.982 | 29.897 | 30.059 | 29.366 | 30.682 | 30.503 |
| 17 | 8.0 | 30.461 | 29.989 | 28.735 | 29.995 | 29.898 | 30.066 | 29.373 | 30.699 | 30.515 |
| 18 | 8.5 | 30.465 | 29.991 | 28.746 | 30.006 | 29.901 | 30.076 | 29.376 | 30.709 | 30.521 |
| 19 | 9.0 | 30.469 | 29.991 | 28.759 | 30.015 | 29.902 | 30.084 | 29.381 | 30.716 | 30.528 |
| 20 | 9.5 | 30.472 | 29.990 | 28.767 | 30.023 | 29.905 | 30.089 | 29.383 | 30.723 | 30.536 |
| 21 | 10.0 | 30.472 | 29.990 | 28.775 | 30.029 | 29.905 | 30.094 | 29.386 | 30.729 | 30.539 |
| 22 | 10.5 | 30.474 | 29.990 | 28.782 | 30.034 | 29.906 | 30.097 | 29.387 | 30.737 | 30.542 |
| 23 | 11.0 | 30.474 | 29.989 | 28.786 | 30.037 | 29.905 | 30.101 | 29.389 | 30.740 | 30.544 |
| 24 | 11.5 | 30.474 | 29.988 | 28.791 | 30.042 | 29.905 | 30.104 | 29.390 | 30.743 | 30.545 |
| 25 | 12.0 | 30.475 | 29.988 | 28.793 | 30.043 | 29.906 | 30.106 | 29.392 | 30.743 | 30.547 |
| 26 | 12.5 | 30.473 | 29.987 | 28.798 | 30.046 | 29.906 | 30.107 | 29.392 | 30.745 | 30.547 |
| 27 | 13.0 | 30.472 | 29.696 | 28.799 | 30.047 | 29.907 | 30.110 | 29.392 | 30.746 | 30.547 |
| 28 | 13.5 | 30.472 | 29.808 | 28.801 | 30.050 | 29.904 | 30.112 | 29.393 | 30.746 | 30.550 |
| 29 | 14.0 | 30.471 | 29.842 | 28.803 | 30.047 | 29.902 | 30.113 | 29.391 | 30.752 | 30.549 |
| 30 | 14.5 | 30.470 | 29.873 | 28.805 | 30.049 | 29.902 | 30.114 | 29.391 | 30.748 | 30.548 |
| 31 | 15.0 | 30.469 | 29.895 | 28.806 | 30.050 | 29.901 | 30.114 | 29.390 | 30.745 | 30.548 |
| 32 | – | – | – | – | 28.806 | 30.049 | 29.901 | 30.111 | 29.390 | 30.743 | 30.546 |
| 33 | – | – | – | – | 28.807 | 30.048 | – | 30.110 | – | – | – |
| 34 | – | – | – | – | 28.807 | 30.047 | – | 30.109 | – | – | – |

**Table 3:** Compilation of the GCV of the waste samples

| S/N | Component | $a$ min | $b$ min | $c$ min | $r_1$ °C/min | $r_2$ °C/min | $?T$ °C | $e_1$ kJ | $e_2$ kJ | $e_3$ kJ | $m$ kg | $C$ kJ /°C | $GCV$ kJ/ kg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Wood | 0.00 | 2.50 | 12.00 | 0.0018 | 0.002 | 1.109 | 0 | 0.00288 | 0.0445 | 1 | 15,000 | 16,580 |
| 2 | Leather | 0.00 | 1.50 | 11.00 | 0.0108 | 0.001 | 1.278 | 0 | 0.0575 | 0.0576 | 1 | 15,000 | 19,050 |
| 3 | Rubber | 0.00 | 2.00 | 15.00 | -0.0036 | -0.001 | 1.493 | 0 | 0.1151 | 0.0802 | 1 | 15,000 | 22,197 |
| 4 | Plastic | 0.00 | 2.00 | 13.50 | 0.0018 | 0.001 | 2.253 | 0 | 0.0115 | 0.0821 | 1 | 15,000 | 33,712 |
| 5 | White paper | 0.00 | 1.00 | 13.00 | 0.006 | 0.0051 | 0.745 | 0 | 0.0050 | 0.0427 | 1 | 15,000 | 14,085 |
| 6 | Bev. Box | 0.00 | 2.50 | 14.50 | 0.0078 | 0.002 | 0.962 | 0 | 0.0921 | 0.0676 | 1 | 15,000 | 14,353 |
| 7 | Textile | 0.00 | 1.50 | 13.50 | 0.0004 | 0.001 | 1.171 | 0 | - | 0.0889 | 1 | 15,000 | 17,476 |
| 8 | PKF | 0.00 | 2.00 | 14.00 | 0.0078 | 0.005 | 1.724 | 0 | 0.00633 | 0.0831 | 1 | 15,000 | 25,771 |
| 9 | PKS | 0.00 | 2.50 | 13.50 | 0.004 | 0.01 | 1.240 | 0 | 0.00633 | 0.0280 | 1 | 15,000 | 18,566 |

It implies that for a given quantity of waste charged into an incinerator the amount of heat released depends to a large extent on the composition of plastic in the feed stock or the overall percentage of hydrogen and carbon. This can be used to determine if auxiliary fuel is required. For a waste composition consisting mostly of rubber, plastic and leather no auxiliary fuel is required for their combustion. The calorific values of wood (16,580 *kJ/ kg*), leather (19,050 *kJ/ kg*), rubber (22,197 *kJ/ kg*) and textile (17,476 *kJ/ kg*) deviate only slightly from the results obtained by Tchobanoglous *et al (*1993), this is due mainly to the differences in moisture content of the solid waste samples.

*Conclusion:* The average calorific value of the waste samples calculated from the experiment is 20,198.89 *kJ/kg*. This is higher than the 7,000*kJ/kg* (Rand *et al*, 2000) minimum average calorific value of waste required for establishing an incineration plant with energy recovery. Hence, this is a clear affirmation that for any project preparation and execution; an experimental framework for justification should be a prerequisite to balance the required analysis. In addition, the estimation of the energy content of municipal solid waste generated in Benin City can be used to establish a mass burn incineration plant with energy recovery in the city.

## REFRENCES

Alter, H (1987). Materials and Energy from Refuse. Crete Journal of Waste Management. 26: 668-679.

Ayhan, D (2004). Determination of Calorific Values of Bio-Chars and Pyro-Oils from Pyrolysis of Beech Trunk barks. Journal of Analytical and Applied Pyrolysis. 2: 215-219

Carlos, FF; Jesus, PL; Joge, A; Rodrigeus, A; Lisardo, NR (1991). Calorific Value of Municipal Solid Waste, Journal of Environmental Technology. 13: 1085 – 1093

Ebru, A (2009). Energy Content Estimation of Municipal Solid Waste by Multiple Regression Analysis. Engineering Principles and Management Issues. McGraw-Hill, New York.

Gabriel, OI (1983). Determination of Calorific Values of Some Nigerian Bio-Mass Solid Materials. Nigerian Journal of Technology. 1: 21 -33.

Gidarakos, E; Havas, G; Ntzamilis, P (2006). Municipal Solid Waste Composition Determination. Journal of Resources and Conservation. 14: 29

Igbinomwanhia, DO; Obanor, AI; Olisa, YP (2014). Characterisation of Domestic Solid Waste for the Determination of Waste Management Option in Amassoma, Bayelsa State, Nigeria. Journal of Applied Science and Environmental Management. 18: 211-215.

Ioannis, G; Panagiotis, X; Dimitrios, K (2016). Experimental Determination of Gross Calorific Value of Different Agroforestry Species and Bio-Based Industry Residues. Journal of Scientific Research. 7: 1-12.

Muñoz, MJ; Guillena, AL; Martinezde, L (1992). Determination of calorific values of coals by differential Thermal Analysis. Journal of Analytical and Applied Pyrolysis. 71 (5): 579-583.

National Population Commission (2006). The Nigerian Population Statistics of 2006. www. Population.gov.ng/index.php (Last accessed on 2/11/2017)

Obernberger, I; Brunner, T; Barnthaler, G (2006). Chemical Properties of Solid Biofuels – Significance and Impact. Journal of Biomass and Bioenergy. 30: 973-982

Rand, T; Haukohl, J; Marxen, U (2000). Inceneration of Solid Waste: A Decision Makers Guide. World Bank, Washinton DC

Tchobanoglous, G; Theisen, H; Vigil, S (1993). Integrated Solid Waste Management. McGraw-Hill, NJ.