ESTIMATING THE ENERGY CONTENT OF MUNICIPAL SOLID WASTE FROM ITS PHYSICAL COMPOSITION: THE HEAT OF COMBUSTION OF PORTO ALEGRE'S HOUSEHOLD SOLID WASTE

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Abstract. *Estimates of the energy content of Porto Alegre's household solid waste were made based on default heating and moisture content values and based on models developed on physical composition analysis. Default values led to an estimation of 41.92% for moisture content, 9.98 MJ/kg for gross heating value (HHV), and 4.77 MJ/kg for net heating value (LHV). Such difference between HHV and LHV are due great portion of water content estimated for observed waste. Results from selected models showed higher heating values, but still close from the minimum level of 7 MJ/kg of net heating value required for incineration projects. Estimates suggest that further analysis on waste moisture content must be conducted.*

Keywords*: waste-to-energy, energy content, municipal solid waste, physical composition analysis*

1. NOMENCLATURE

Fo	Percentage of food waste [%]
HHV	Higher heating value, wet mass content [MJ/kg]
HHV_d	Higher heating value, dry mass content [MJ/kg]
LHV	Lower heating value [MJ/kg]
M	Moisture content, mass fraction decimal [-]
Or	Percentage of organic material (food, wood and grass) [%]
Pa	Percentage of paper/cardboard [%]
Pl	Percentage of plastic [%]
W	Moisture content [%]

2. INTRODUCTION

In August 2010 entered into force the Brazilian Policy on Solid Waste, establishing principles relating to the integrated and environmentally suitable management of national solid waste (Brasil, 2010). It establishes that until August 2014 it must be set the following waste management hierarchy: no generation, reduction, reuse, recycling, treatment, and environmentally suitable disposal. Environmentally suitable disposal is defined as the distribution of post-treated waste (refuse) in well-engineered landfills observing specific operational norms in order to avoid damage or risk to public health and safety and aiming at the minimization of adverse environmental impact. Refuse is defined as solid waste of which, once all recovery and treatment possibilities through available technological and economically viable processes have been exhausted, presents no other possibility than environmentally suitable disposal. This means that non-recycled waste must be treated and only refuse should be landfilled. The Policy foresees the use of technologies for energy recovery, as long as it has been proven its technical and environmental feasibility and as long as an air emissions monitoring program, approved by the environmental agency, is implemented.

Energy recovery treatment technologies by waste burning are known as waste-to-energy (WTE) (WTERT, 2012). WTE facilities use waste products as a fuel for the production of thermal energy. The most common process is combustion (incineration). There are around a hundred municipal solid waste (MSW) power plants worldwide, the vast majority in the United States (International Database of Waste-to-Energy Plants, 2012). In order to evaluate the feasibility of energy recovery as an integral part of a solid waste management system, it is of great importance to determine the energy content of the waste, which is defined as the number of heat units evolved when unit mass of material is completely burned and is a function of many parameters, namely, physical composition of the waste, moisture content and ash content (Abu-Qudais and Abu-Qdais, 2000). The heat of combustion can be determined experimentally by a bomb calorimeter or estimated from fuel's properties using a mathematical model (Thipkhunthod *et al.,* 2005). Solid waste can vary widely in composition and physical characteristics, making parameters of combustion troublesome to predict (Tchobanoglous and Kreith, 2002). Considering operation practices, it is quicker and cheaper to predict heating value by employing a model based on physical composition analysis (Chang *et al.,* 2007). This paper reviews available models and compares its results on the estimation of the energy content of the household solid waste from the city of Porto Alegre (Rio Grande do Sul, Brazil).

3. METHODOLOGY

A first approach on putting on a predictive equation to estimate the energy content of municipal solid waste is to analyze its physical composition and to multiply the percentage of each waste component by its default heating value. Such values can be found in literature as in Komilis *et al.* (2012) and Tchobanoglous and Kreith (2002). According to Dong *et al.* (2003), the energy content of MSW has strong relationship with weight percentages of plastic, paper, food, grass, and textile. It must be noted that default heating values usually refer to the gross (higher) heating value resulting from measurements in bomb calorimeters. It must also be noted if values are expressed on a per wet or per dry mass content of component basis. In order to assess dry weights, default moisture content values must be subtracted from observed wet weights (dry weight plus moisture content equals total weight). Energy content decreases with fuel's water content, as portion of the combustion heat is used up to evaporate moisture. Resulting values of HHV are related as shown in Eq. (1) (Sokhansanj, 2011).

$$HHV = (1 - M)HHV_d \tag{1}$$

Several empirical models have been developed to describe and predict the energy content of MSW. A bibliographic research on published models that correlate the energy content of MSW with its physical composition was carried out in the Elsevier's ScienceDirect scientific database (*http://sciencedirect.com*). Keywords searched were: heating value, heat of combustion, energy content, energy value, calorific value, waste, waste-to-energy. Three out of nine found models were selected for this study, as original data is reported:

- Abu-Qudais and Abu-Qdais (2000), estimation of the energy content of MSW generated in Jordan (16% plastic, 11% paper, 63% food, 60% moisture content, average gross heating value 11.5 MJ/kg) , Eq. (2)

$$HHV = 0.004\left[267.0\left(Pl / Pa\right) + 2285.7\right] \tag{2}$$

- Kathiravale *et al.* (2003), estimation of the energy content of MSW generated in Malaysia (21% plastic, 11% paper, 52% food, 4% grass, 2% textile, 55% moisture content, average gross heating value 17 MJ/kg) , Eq. (3)

$$HHV = 0.001\left[112.157Fo + 183.386Pa + 288.737Pl + 5064.701\right] \tag{3}$$

- Usón *et al.* (2012), estimation of the energy content of the residual fraction refused by Zaragoza's mechanical-biological treatment plant (19% plastic, 25% paper, 22% food/grass/wood, 7% textile, average gross heating value 18 MJ/kg) , Eq. (4)

$$HHV = 0.001\left[112.815Or + 184.366Pa + 298.343Pl - 1.920W + 5130.380\right] \tag{4}$$

Equations predict higher heating values (HHV, gross). HHV assumes that all of the water in the products has condensed to liquid and LHV assumes that none of the water has condensed. HHV scenario liberates the most amount of energy, as condensation is an exothermic reaction; hence values are higher than LHV (Turns, 2000). The LHV is a better measure than the HHV of the heat released by the waste under actual operating conditions, however in most instances only HHV is reported. HHV includes the heat of condensation of water vapor formed in the combustion reaction, which is not realistic for industrial combustion equipment, as water in the final combustion products remains as vapor (Cooper *et al.*, 1999). An estimate of the LHV is obtained from the measured HHV by subtracting the heat of vaporization of water in the products, as shown in Eq. (5). Calculation considers wet weight, heating values at constant pressure, the wet basis moisture content in mass fraction decimal, and the latent heat of vaporization of water (Sokhansanj, 2011). The difference between HHV and LHV depends mainly on the hydrogen content of the fuel. For most biomass feedstocks this difference appears to be 6–7% (Oak Ridge National Laboratory, 2012).

$$LHV = HHV(1 - M) - 2.443M \tag{5}$$

Results on the estimation of the energy content of the household solid waste from the city of Porto Alegre were analyzed. Household solid waste refers to the general waste stream from the ordinary municipal collection service (waste not disposed for the recycling municipal collection service). Characterization from Fleck and Reis (2011) reports the following physical composition of Porto Alegre's disposed waste: 57.27% of organic material, 11.61% of paper and cardboard, 11.22% of plastics, 3.39% of textiles, 2.56% of glass, 1.46% of metals, 12.49% other components. Percentages represent observed wet weight. In order to assess the total waste moisture content, default moisture content values were subtracted from observed wet weights.

4. RESULTS

Table 1 shows physical composition of Porto Alegre's disposed waste, component's default heating and moisture content values and estimated energy content. Waste composition data is from Fleck and Reis (2011) and default heating and moisture content values are from Komilis *et al.* (2012) and Tchobanoglous and Kreith (2002). Components classified as "other" were assumed to have 5% moisture content and no heating value. Default values led to an estimation of 41.92% for moisture content, 9.98 MJ/kg for HHV, and 4.77 MJ/kg for LHV (48% of HHV). Such difference between HHV and LHV are due great portion of water content estimated for observed MSW.

Table 1. Estimation of the energy content of Porto Alegre's household solid waste by default heating and moisture content values.

Component	Observed weight [%]	Default moisture content [%]	Estimated dry weight [%]	Default gross heating value [MJ/kg] (HHV, wet weight)	Estimated contribution [MJ/kg] (HHV, wet weight)
Organic material	57.27	70.00	17.18	4.65	2.66
Paper wastes	11.61	6.23	10.89	15.24	1.77
Cardboard	2.23	4.30	2.13	16.78	0.37
Kitchen paper	2.85	6.00	2.68	15.28	0.44
Office paper	1.04	5.50	0.98	11.96	0.12
Tetrapack	1.36	8.00	1.25	16.11	0.22
Magazines	0.73	4.80	0.69	11.58	0.08
Newsprint	3.40	7.50	3.15	15.60	0.53
Plastics	11.22	0.41	11.17	44.04	4.94
PETE	1.39	0.23	1.39	22.81	0.32
Rigid plastic	3.13	0.21	3.12	49.10	1.54
Flexible plastic	6.21	0.54	6.18	46.70	2.90
PVC	0.08	0.46	0.08	18.96	0.02
Expanded PS	0.41	0.57	0.41	41.89	0.17
Textiles	3.39	10.00	3.05	17.45	0.59
Glass	2.56	2.00	2.51	0.14	0.00
Metals	1.46	3.00	1.42	0.70	0.01
Other	12.49	5.00	11.87	0.00	0.00
Overall	**100.00**	**41.92**	**58.08**	**-**	**9.98**
Estimated net heating value (LHV) [MJ/kg]					**4.77**

Table 2 shows results from selected models developed on physical composition analysis. Heating values were higher than previous estimation, except for Eq. (2) in which values were close. Such model only accounts paper and plastic wastes, and original content data are similar from ones observed in Porto Alegre.

Table 2. Estimation of the energy content of Porto Alegre's household solid waste by models developed on physical composition analysis.

Model	Estimated gross heating value (HHV) [MJ/kg]	Estimated net heating value (LHV) [MJ/kg]
Eq. (2), Abu-Qudais and Abu-Qdais (2000)	10.64	5.16
Eq. (3), Kathiravale *et al.* (2003)	16.86	8.77
Eq. (4), Usón *et al.* (2012)	17.01	8.85

The successful outcome of a waste incineration project depends on fairly accurate data on the future waste quantities and characteristics that form the basis for the design of the incineration plant; therefore waste for incineration must meet certain basic requirements. In particular the energy content of the waste must be above a minimum level. The average LHV must be at least 6 MJ/kg throughout all seasons and the annual average LHV must not be less than 7 MJ/kg (The World Bank, 1999). Estimates of the energy content of Porto Alegre's MSW observed in this study suggest that further analysis on waste moisture content must be conducted. Hydrothermal treatment has attracted interests as a possible application producing coal-like solid fuel from MSW and biomass resources with high moisture and oxygen contents, demonstrating improvement of dehydration and drying performances as well as fuel upgrading (Kim *et al.*, 2012).

5. CONCLUSION

Estimates of the energy content of Porto Alegre's household solid waste were made based on default heating and moisture content values and based on models developed on physical composition analysis. Default values led to an estimation of 41.92% for moisture content, 9.98 MJ/kg for higher heating value, and 4.77 MJ/kg for lower heating value (48% of HHV). Such difference between HHV and LHV are due great portion of water content estimated for observed MSW. Results from selected models showed higher heating values, but still close from the minimum level of 7 MJ/kg of net heating value required for incineration projects. Estimates suggest that further analysis on waste moisture content must be conducted.

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