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Effect of organic matter and moisture on the calorific value of solid wastes: An update of the Tanner diagram

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ABSTRACT

Objective of the work was to experimentally determine the effect of the organic matter and moisture contents on the calorific value of organic solid wastes. Nine substrates (i.e. newsprint, biodried municipal solid wastes, municipal solid waste derived composts, wastewater sludges, and sea weed derived compost), with organic matter contents that ranged from 12% to 91% (dry weight) were used in the experiments. All substrates were dried and ground and deionized water was artificially added in order to achieve certain target moisture contents per substrate. The higher heating value (HHV) was, then, determined experimentally for each sample using a bomb calorimeter. Best reduced models were developed to describe the higher and lower heating values as a function of organic matter, ash and moisture contents. A triangular plot was constructed and the self-sustained combustion area was determined and compared to that of the Tanner diagram. Response surfaces were drawn to visually assess the effect of organic matter and moisture contents on the calorific value of the wastes.

1. Introduction

Incineration is a common technique to treat municipal solid wastes (MSW); it aims to both recover energy and to drastically minimize waste volume and mass. It is also a technology preferable in countries where there is lack of a space and where land value is high. According to Eurostat (2011), the amount of wastes directed to incineration has risen by 63% from 1995 to 2009, being the third, after landfilling and recycling, applied MSW treatment option. Based on data from 32 European countries (including the 27 EU member states), incineration was used to treat 20% of the generated MSW in 2010 (EEA, 2013). Countries such as Denmark, Sweden and Switzerland are the leaders in the use of that technology by incinerating a little more than 40% of their MSW generated in 2009 (Eurostat, 2011).

According to directive 2008/98/EC (EC, 2008), MSW incineration can be categorized either as a disposal or an energy recovery technology depending on the energy efficiency of the incinerator (EC, 2008). The energy efficiency of a MSW incinerator can be calculated according to the R1 formula (EC, 2008; Grosso et al., 2010). One of the input parameters in the R1 formula is the calorific value (CV) of the waste mixture. Although calorimetric measurements are always preferred, a rapid method is often pursued in order to make a first assessment of both the energy content and the self-sustained combustibility of the waste stream. Both these aspects are directly related to the economic viability of the incineration project. For example, the absence of self-sustained combustibility requires the use of external fuel (a parameter that is accounted for in the R1 formula), which will result in the reduction of the overall energy efficiency of the incineration plant.

It is common knowledge that moisture affects the self-sustained combustibility and calorific value of municipal solid wastes (MSW). As moisture increases, the calorific value of a material decreases due to the heat of vaporization of water (latent heat of water). According to the World Bank report (World Bank, 1999, pp. 9), MSW should normally have an annual average CV of at least 7 MJ/wet kg to render their incineration viable. Other viability criteria, according to the same report, are that the average calorific value should not be less than 6 MJ/kg throughout all seasons and that the MSW input rate to an incinerator should not be less than 50,000 t/y.

The CV is normally classified into the lower heating value (LHV) and the higher heating value (HHV). The former is obtained when the water evaporated from the combustion remains as steam and does not condense back to liquid water after combustion. The latter is obtained when the evaporated water condenses back to liquid water. Therefore, HHV is always greater than LHV, unless a material is completely dry and contains minimal elemental hydrogen. HHV is usually measured experimentally by bomb calorimeters, although there are theoretical equations to calculate it, usually as a function of the ultimate (elemental) analysis of a substrate (Komilis et al., 2012). LHV is calculated theoretically as a function of the HHV and the moisture content of a substrate

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(Abu-Qudais and Abu-Qdais, 2000; Komilis et al., 2012). Elemental hydrogen has been proposed as an additional LHV predictor (Cooper et al., 1999; Koufodimos and Samaras, 2002), since hydrogen oxidizes to water during combustion. Although LHV is a theoretical number, it has a more practical application than HHV, since it is the energy that is actually exerted and utilized in a MSW incinerator.

One of oldest, yet still used, graphical plots to assess the self-sustained combustibility of MSW is the Tanner diagram (Tanner, 1965). The Tanner diagram (Fig. 1) is a triangular plot with the 3 axes being the combustibles (organic matter or volatile solids), the ash and the moisture. All these 3 variables have to be expressed on a wet weight basis (wb), which is a precondition to draw a triangular plot, since it is based on the principles of mixture experimental designs (Montgomery, 2005, pp. 444–454). Therefore, each location within a Tanner diagram represents a solid waste mixture in which the sum of the Organic Matter (OM) content (% wb), the Ash (A) content (% wb) and the Moisture (M) contents (% wb) should always equal 1 (or 100%). The proposed self-sustained combustibility of MSW is the shaded area within the Tanner diagram (see Fig. 1). According to the diagram, MSW mixtures with ash content $\leqslant$ 60% (wb), water content $\leqslant$ 50% (wb) and combustible (organics) content $\geqslant$ 25% can maintain self-sustained combustion without the support of external fuel. Mixtures outside the shaded area can still burn but with the support of external fuel.

The Tanner diagram was based on a 1965 report and was constructed using field data from actual MSW incinerators from several parts of the world (Tanner, 1965). The diagram fails, however, to depict the change of calorific values within the area of self-sustained combustion (shaded area). For example, it is expected that the higher the organic matter (combustible) content and the lower the ash and moisture contents, the higher the calorific value is. To the opinion of the authors, the Tanner diagram could have been alternatively depicted as a plain 2 axis (2D) plot, with only OM and M appearing on the axes, since ash is directly dependent on the organic matter content (i.e. ash is always 1 minus the organic matter or combustible content).

The objective of this study was to check the validity of, and update, the Tanner diagram using laboratory measurements with various organic substrates, such as different wastewater sludges, organic composts and certain MSW components. An additional aim was to develop regression equations and to draw response surfaces in order to empirically describe the calorific value as a function of the organic matter, moisture and ash contents. Results of this work can be used as an assessment tool to evaluate the self-sustained combustion of a mixture of wastes and to calculate their

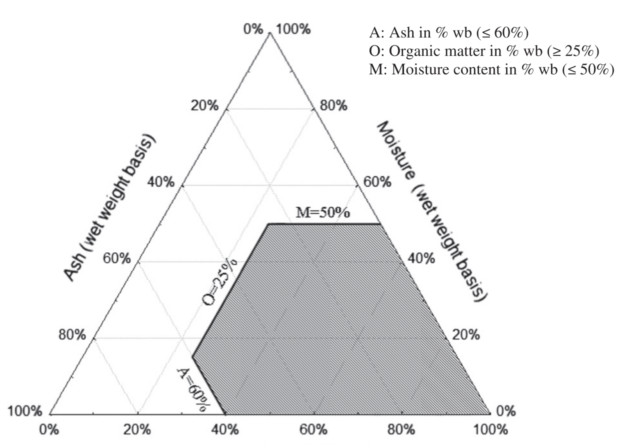

Fig. 1. The traditional Tanner diagram as used to assess the self-sustained combustibility (shaded area) of municipal solid wastes during incineration (Tanner, 1965).

calorific value by simply using their initial organic matter and moisture contents.

2. Materials and methods

2.1. Substrate sampling

Nine organic substrates were used in this work (see Table 1), so that to obtain a wide range of organic matter contents, from a low 12% on a dry weight basis (db) to a maximum 91% (db). Specifically, the substrates used in this work were:

(i) Old newsprint (NSP) that had the highest OM content at 91% (db) among all substrates.
(ii) Biodried MSW (BD_MSW) that were obtained from the outlet of the sole commingled MSW biodrying facility in South Greece (Heraklion, Crete). The sampling was performed via quartering right after the removal of ferrous materials at the outlet of the plant. A 12 kg wet sample was transferred to the university laboratory.
(iii) Three MSW composts at variable stages of aerobic decomposition (MSWC_L, MSWC_1, and MSWC_2). Two MSW composts were obtained from a small scale mobile MSW composting unit in South Greece (Kalamata). The commingled MSW, there, first passed through a shredder, a trommel screen and, then, through a 7-day intensive aeration period plug flow type reactor. The substrates were obtained from the curing piles. A third MSW compost was obtained from the curing piles of an aerobic mechanical and biological pretreatment facility in Athens (Greece).
(iv) Three wastewater sludges (SLD_DWK, SLD_DRD, and SLD_DRK) with variable OM and initial moisture contents (i.e. one dewatered sludge and two dewatered/dried sludges). The sludges were obtained from two wastewater treatment plants (WWTP) located in the Region of Eastern Macedonia and Thrace in North Greece (Komotini, Drama). The two sludges were collected from the same facility; one was dewatered via a filter press, whilst the other was dewatered via a filter press and then dried in drying beds. The 3rd sludge was also dewatered (via a filter press) and then dried.
(v) A sea weed derived compost (SWC), with the lowest OM content (11.9% db) among all substrates. This was a marketable product that was purchased from a local agricultural store.

Plastics and food wastes were not used in the experiments, since it was not feasible to obtain a homogenized mixture of the above components with water.

All aforementioned substrates were subjected to additional quartering to obtain a random sample of around 500 g from each substrate. Then, all substrates were dried at 75 °C until constant weight and their initial moisture content was calculated via weight difference. The dried substrates were then ground using a cutting mill by RETSCH® (Germany) that was equipped with a 1.5 mm mesh size screen. Organic matter (OM) was measured via weight difference at 550 °C for 2 h and the total C content was measured with an elemental analyzer (Thermo-Electron, USA, model: EA-1110, CHNS-O) according to Komilis et al. (2012).

2.2. Experimental design and calorimetric measurements

The experimental design is included in Table 1. After drying and grinding all substrates, wetting was performed using the appropriate amounts of water so that to reach the target moisture contents (in% wb), as shown in Table 1. The amount of water (x) that was