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Element partitioning in combustion- and gasification-based waste-to-energy units

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ABSTRACT

A critical comparison between combustion- and gasification-based waste-to-energy systems needs a deep knowledge of the mass flows of materials and elements inside and throughout the units. The study collected and processed data from several moving grate conventional incinerators and high-temperature shaft gasifiers with direct melting, which are in operation worldwide. A material and substance flow analysis was then developed to systematically assess the flows and stocks of materials and elements within each waste-to-energy unit, by connecting the sources, pathways, and intermediate and final sinks of each species. The patterns of key elements, such as carbon, chloride and heavy metals, in the different solid and gaseous output streams of the two compared processes have been then defined. The combination of partitioning coefficients with the mass balances on atomic species and results of mineralogical characterization from recent literatures was used to estimate a composition of bottom ashes and slags from the two types of waste-to-energy technologies. The results also allow to quantify some of the performance parameters of the units and, in particular, the potential reduction of the amount of solid residues to be sent to final disposal.

1. Introduction

The municipal solid waste (MSW) management systems that operate successfully worldwide demonstrate the key role of thermal treatment, which appears essential to obtain the environmental and economic sustainability of the whole system (Psomopoulos et al., 2009; Brunner, 2012). The environmental impact of modern, adequately constructed and operated, waste-to-energy (WtE) units is today assessed as comparable to that of a medium industry (Rechberger and Schöller, 2006), and anyway less "than almost any other source of electricity" (US-EPA, 2003). Nevertheless, fear of pollution still brings WtE plants to the center of emotional public debate, much of it based on perception rather than on objective scientific evidence. This public perception forces the manufacturers of WtE plants to continuously improve the performance of the chemical conversion process and to develop advanced technologies for pollution control systems (Arena et al., 2012; ESA, 2012).

With specific reference to the chemical conversion process, the whole range of technologies can be grouped into two main categories: combustion- and gasification-based thermal treatment. The first is a well established and sustainable technology that results in considerable waste volume reduction with the added ability to reclaim a significant amount of energy. There are more than 900 plants in operation, having a capacity that ranges from 50 to 1000 kt/y: the most common type of combustion-based WtE technology used worldwide is the mass burn moving grate incinerator (Stantec, 2011; ESA, 2012). The second involves more complex processes and is less proven on a commercial scale, even though about 100 gasification-based WtE plants, having a capacity that ranges from 10 to 250 kt/y, are today in continuous operation, mainly in Japan but also in Korea and Europe. This suggests that gasification could today be proposed as a viable alternative for a WtE treatment, particularly if a dramatic reduction of the amount of residues to be disposed in landfills is required (Arena, 2012).

The paper aims to provide data for a critical comparison between a combustion- and a gasification-based process (in the following indicated as CB-WtE and GB-WtE), on the basis of a detailed analysis of the mass flows of materials and elements inside and throughout the units. The study focuses on the thermal treatment of the same municipal solid waste in a moving grate combustor and in a high-temperature vertical shaft gasifier with melting system, respectively. To this end, a large collection of data from several units in operation were processed by means of different analytical tools. In particular, a Material Flow Analysis (MFA) and a Substance Flow Analysis (SFA) have been carried out by means of the freeware STAN (subSTance flow ANalysis) developed by the Vienna University of Technology (Cencic and Rechberger, 2008). The MFA is a systematic assessment of the flows and stocks of materials and elements within a system defined in space and

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time (Brunner and Rechberger, 2004; Brunner, 2004), which is named SFA when it is referred to a specific chemical element. SFA is today largely utilized to link inputs and outputs of treatment process and management systems, so supplying data that are often relevant for the design, operation, and control of waste treatment systems. In a framework of increasing complexity of solid waste composition (Brunner, 2012), its ability to connect the sources, pathways, and intermediate and final sinks of each species in a specific process appears greatly attractive, as demonstrated by its utilization in the assessment of recycling options (Rotter et al., 2004), waste management scenarios (Morf and Brunner, 1998; Mastellone et al., 2009; Arena and Di Gregorio, 2012) and specific thermal treatments (Brunner and Mönch, 1986; Arena et al., 2011).

A combined MFA and SFA has been utilized in this study to define and compare the patterns of some key elements of municipal solid waste throughout the different sections of the two compared WtE plants. A particular attention was dedicated to the partitioning of low-boiling-point heavy metals and to their concentration in output solid streams with reference to reuse or disposal scenarios. It is in fact recognized that the recovery of metals and inert materials from waste-to-energy solid residues can become a crucial issue, from both environmental and economic point of view. It defines the possible recovery of valuable materials such as copper, iron and aluminum (Meawad et al., 2010; Rocca et al., 2012) and, above all, the reduction of the amount of residues to be sent to final disposal. This aspect is becoming crucial since the shortage of traditional disposal sites, together with stricter requirements for location and more severe environmental controls, have resulted in a strong reduction of the number of adequate sites for safe landfills, especially in areas at high density of population (Heller and Catapreta, 2003; UNEP, 2012).

2. Waste composition and WtE configurations

The fraction of MSW which is typically treated in a WtE unit is that residual from the operations of source separation and collection of dry recyclable and wet organic fractions. It is typically called unsorted residual waste (URW), and its composition varies widely between countries and within each country, depending on some factors such as the local standard of living and (quantitative and qualitative) levels of household separation and collection. This variation may affect the set of optimal operating parameters of the unit as well as the amount and characteristics of produced solid residues; rarely it can also affect the emission of pollutant species. Taking in mind these considerations, the waste composition utilized in this investigation is that reported in Table 1, as obtained by the Confederation of European Waste-to-Energy Plants as average data from 29 European States (Kreißig and Stoffregen, 2008; CEWEP, 2009).

The comparative analysis of combustion- and gasification-based waste-to-energy processes was then developed with reference to the most utilized technologies for each WtE category, i.e. the moving grate furnace and the high temperature shaft reactor with direct melting (Arena, 2012). The first is the predominant mass burning technology: only in Europe it is utilized by 420 of the total 450 incinerators in operation. It is a well known and reliable type of furnace, with defined design and operating criteria (Stantec, 2011), even though new advanced solutions are continuously developed to improve the already high energetic and environmental performances (Gartner, 2011). The selected gasification-based technology is that most utilized in MSW gasification processes, with more than 40 units in operation. It is a high temperature gasification and melting reactor, with O_2-enriched air injection in the melting section and the solid waste charged from the top of the vertical shaft furnace, together with coke and limestone (Tanigaki et al., 2012; Suzuki and Nagayama, 2011). A coke bed layer is formed in the lower part of the direct melting furnace and it is burned and kept at high temperatures in order to melt ash stably, to prevent cool-down of slag and accelerating waste thermal devolatilization and gasification. Limestone is added to provide some pH buffering of the melt and to form fluid slag that can be easily discharged from the furnace bottom. In some plants, a natural gas or LPG injection system is utilized to improve the carbon conversion ratio of the injected char (Tanigaki et al., 2008). From the top to the bottom of the gasifier it is possible to individuate a drying and pre-heating region (which operates at about 400 °C), a thermal decomposition region (between 600 and 800 °C) and a combustion and melting region (between 1000 and 1800 °C). The produced syngas is transferred to a swirling combustor that transfers the generated thermal energy to a boiler, which in turn powers a steam turbine that produces electricity (Arena, 2012).

The schematic configurations of the two WtE plants are reported in Figs. 1 and 2: both of them include similar heat recovery and air pollution control (APC) systems, so that the potential different performances could be mainly ascribed to the different conversion technologies. An accurate analysis has been carried out to define the set of values of the main operating parameters and that of reagent consumptions. The most important of them are listed in Table 2: for the CB-WtE unit the main sources were the Best Reference Document of European Community on Best Available Technologies for Waste Incineration (EC-IPPC, 2006), together with reports from several plants in operations, particularly in Italy and United Kingdom (C-Tech, 2003; CEWEP, 2009; Federambiente and Enea, 2012); for the GB-WtE unit the main sources were the scientific literature about large-scale plant operating experience (Tanigaki et al., 2008; Tanigaki et al., 2012), together with the results of a recent investigation about combustion- and gasification-based WtE units in Japan that also analyzed 15 gasification and melting systems (Matsuto, 2012). Some of these sources (Kreißig and Stoffregen, 2008; CEWEP, 2009; Tanigaki et al., 2008) contain also data of performances of the different sections

Table 1
Ultimate analysis and LHV of the unsorted residual waste assumed as reference. Source of data: CEWEP (2009).

Element	Concentration ($kg/t_{wet\ waste}$)	Element	Concentration ($kg/t_{wet\ waste}$)	Element	Concentration ($kg/t_{wet\ waste}$)	Element	Concentration ($kg/t_{wet\ waste}$)
Ag	0.00017	Co	0.002	Mn	0.33	SiO_2	99
Al	10	Cr	0.19	N	8.4	Sn	0.012
As	0.01	Cu	1.1	Na	4.4	Sr	0.000024
Ba	0.0000072	F	0.064	Ni	0.11	Te	0.00047
Be	0.00047	Fe	24	O	180	Ti	0.39
Br	0.00011	H	40	P	0.76	Tl	0.000046
C	250	Hg	0.0004	Pb	0.2	V	0.012
Ca	20	K	3.3	S	1.3	Zn	0.72
Cd	0.014	Mg	2.9	Sb	0.0071	*H_20*	*340*
Cl	3.6	Mo	0.00047	Se	0.000094	*Ash*	*240*

Low Heating Value = 9.8 MJ/kg.