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Oxidation and waste-to-energy output of aluminium waste packaging during incineration: A laboratory study

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ABSTRACT

This work reports the oxidation behaviour and waste-to-energy output of different semi-rigid and flexible aluminium packagings when incinerated at 850 °C in an air atmosphere enriched with 6% oxygen, in the laboratory setting. The physical properties of the different packagings were determined, including their metallic aluminium contents. The ash contents of their combustion products were determined according to standard BS ISO 1171:2010. The net calorific value, the required energy, and the calorific gain associated with each packaging type were determined following standard BS EN 13431:2004. Packagings with an aluminium lamina thickness of >50 μm did not fully oxidise. During incineration, the weight-for-weight waste-to-energy output of the packagings with thick aluminium lamina was lower than that of packagings with thin lamina. The calorific gain depended on the degree of oxidation of the metallic aluminium, but was greater than zero for all the packagings studied. Waste aluminium may therefore be said to act as an energy source in municipal solid waste incineration systems.

1. Introduction

Aluminium is used in a wide range of packaging applications, from beverage and food cans, to aerosol containers, tubes, foil trays, capsules, lids, wraps, and (together with other materials) blister packs, pouches and laminated cartons. The latter examples might – depending on their aluminium content – also be defined as plastic or paper/carton packaging.

The light weight, strength, attractive metallic look and plasticity of aluminium, the total barrier to light, gasses and moisture that it poses, and its recyclability, make it a preferred material for packaging foods and drinks. It is also very acceptable to consumers and held in high regard by recyclers.

According to the European Aluminium Association (EAA), 17% of all aluminium consumed in Europe is used in the manufacture of packaging. Rigid containers (beverage and food cans, aerosol containers, etc.), with a wall thickness of >200 μm make up some 54% of this total, flexible packaging (foil and laminated foil) with a thickness of <50 μm accounts for some 28%, and semi-rigid packaging (trays, food and pet food trays, tubes, closing systems) with a thickness of 50–200 μm make up some 18% (EAA, 2011).

In 2013, the EU produced around 2.4×10^8 tonnes of municipal solid waste (MSW) (Eurostat, 2014a), of which some 5.8×10^7 tonnes was treated at incineration (waste-to energy [WtE]) plants (Eurostat, 2014b). In Spain, the production of MSW runs to nearly 2.2×10^7 tonnes per year, of which some 2.1×10^6 tonnes are incinerated at 10 WtE plants (Eurostat, 2014b). Aluminium packaging waste makes up around 3% of all MSW in the EU (EAA, 2011), i.e., some 7.2×10^6 tonnes. A recent study by ARPAL (Arpal, 2013) reports that Spain produces some 42,395 tonnes of aluminium packaging waste per year, of which some 28,000 tonnes are incinerated. Around 81 wt.% correspond to rigid packagings (cans, aerosol cans, bottles and containers, etc.), 9 wt.% to semi-rigid packagings (food trays, etc.), and 10 wt.% to flexible packagings (blister packs, laminae, foils and packets, etc.).

Since aluminium melts at 660 °C, and the typical operating temperature of oxygen-enriched atmosphere MSW incinerators is 850 °C, a certain fraction of the aluminium content of any waste will melt and oxidise (the actual amount depending on the type and thickness of the material involved) (Calder and Stark, 2010). The oxidation of aluminium involves an exothermic reaction with oxygen (molar enthalpy of oxidation [ΔH^0_{298K}] 1675.7 kJ/mol), as shown in Eq. (1):

$$2Al_{(metal)} + 3/2O_{2(gas)} = Al_2O_{3(solid)} \qquad (1)$$

The aluminium itself may become partially or fully coated by a layer of Al_2O_3. When very thin aluminium packaging combusts in the incinerator's chamber, the small particles of aluminium oxide produced are removed by the flue gas control system (Hu et al., 2011). The aluminium contained in thicker materials, however, will concentrate in the bottom ash (Pruvos, 2013). Among this

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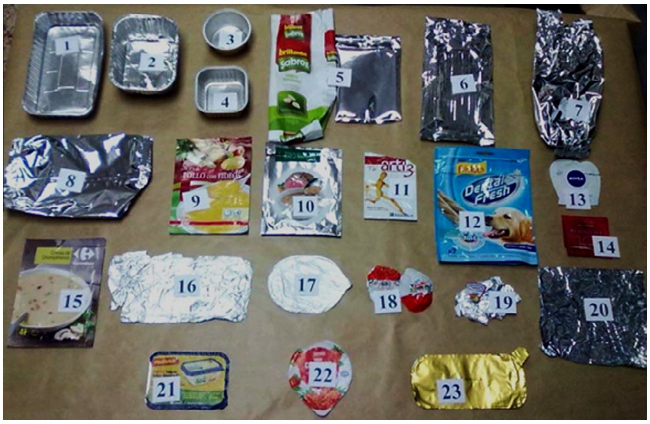

Fig. 1. The studied packaging samples (samples 1–4 – semi-rigid packagings; samples 5–15 – flexible with low Al content; samples 16–23 – flexible with high Al content).

Table 2
Ash content and aluminium transformed into Al_2O_3 (mean values).

Packaging format	Ash (wt.%)	Al_2O_3 (wt.%)
Semi-rigid (samples 1–4)	95.2 ± 4.9	0.8 ± 0.6
Flexible A[a] (samples 5–15)	10.7 ± 9.6	3.9 ± 6.4
Flexible B[b] (samples 16–23)	86.2 ± 10.8	9.4 ± 9.9

[a] Low Al content.
[b] High Al content.

ash it is also common to find the remains of intact aluminium packagings, the surfaces of which have been oxidised (Biganzoli et al., 2012). It should be remembered that Al_2O_3 is a refractory product that can protect unmelted aluminium from further oxidation, even when the ash is cooled quickly with cold water (a practise followed at most incinerators in Europe).

According to the CEN standard on energy recovery (BSI, 2004), thin gauge aluminium foil (up to 50 μm thick) is recoverable in the form of energy, meaning that it is fully oxidised, However, the oxidation and volatilisation rates of aluminium metal waste in incineration furnaces are not well known. One way of examining them is via the use of empirical equations, which allows the heat released by different types to be calculated under different operating conditions. One such equation is provided by standard BS EN 13431:2004 (BSI, 2004). This standard is assumed to be fulfilled when Q_{net} (net calorific value at a constant pressure and volume, defined in BSI, 2009) exceeds the amount of required energy (H_a) to adiabatically raise the temperature of the post-combustion products (including excess air) from ambient temperature to the specified final temperature. The calorific gain is expressed via Eq. (2):

$$\text{Calorific gain} = Q_{net} - H_a \tag{2}$$

The Q_{net} of a packaging made up of different components can be determined via Eq. (3):

$$Q_{net} = \sum_{i=1}^{n} f_i Q_{net,i} \tag{3}$$

where f_i is the mass fraction of each constituent "i" of the packaging and Q_{net},$_i$ is the net calorific gain at a constant pressure and volume of each constituent "i".

The aluminium remaining in the ash after incineration at 850 °C for 1 h can be determined using standard BS ISO 1171:2010 (BSI, 2010), via Eq. (4)

$$\text{Ash (wt.\%)} = (G_1/G_2) \cdot 100 \tag{4}$$

where G_1 is the mass of the waste following incineration, and G_2 the initial mass.

The energy required to adiabatically heat the combustion products, residues and excess air from T_0 to T_a is determined according to standard BS EN 13431:2004 (BSI, 2004) using Eq. (5):

$$H_{a,i} = \sum_{j=1}^{m} g_j C_{pj} (T_a - T_0) \tag{5}$$

where g_j represents the ratio of the combustion products and residues (flue gas and ashes) and excess air (j) resulting from the amount of constituent "i" in the packaging, C_{pj} is the specific heat capacity of the post-combustion products "j" at constant pressure, and T_a and T_o are the final adiabatic temperature and room temperature respectively.

Theoretically, for flexible aluminium packaging with a thickness of <50 μm, an H_a value of 6.4 MJ/kg would be obtained via the use of Eq. (5) (contemplating a heat capacity for aluminium of 897 kJ kg^{-1} K^{-1}, and one of 915 kJ kg^{-1} K^{-1} for oxygen at 1 atm. Using Eq. (2), the calorific gain for the flexible aluminium packaging would theoretically be 24.6 MJ/kg; this value is obtained understanding Q_{net} to equal 31 MJ/kg and H_a 6.4 MJ/kg (BSI, 2004). When the heat losses for the incinerator are taken into account (25% according to standard BSI, 2004), a heat gain of 23.3 MJ kg^{-1} is obtained.

But is this really what happens? How do other aluminium packagings behave during incineration? Does aluminium waste really provide a WtE output during incineration?

The aim of the present work was to study the behaviour of different types of aluminium packaging when subjected to incineration temperatures in an oxidising atmosphere and to determine whether they provide energy to incineration systems.

2. Experimental

2.1. The studied packagings

The studied wastes were 23 types of semi-rigid and flexible aluminium packaging (samples selected by Ecoembalajes España S.A. during 2014), obtained at Spain's 10 MSW incinerator plants (Fig. 1).

2.2. Separation and characterisation of the different waste components

The metallic aluminium content of each packaging type was determined via the selective dissolution of the metal in 1 M HCl

Table 1
Physical properties (mean values) of the studied packagings.

Packaging formats	Weight (g)	Surface density (kg/cm^2)	Thickness of Al lamina (μm)	Metallic Al (wt.%)	Polymers (wt.%)	Cellulose (wt.%)
Semi-rigid (samples 1–4)	5.6 ± 1.4	0.22 ± 0.05	72.8 ± 14.1	94.8 ± 4.7	5.2 ± 5.4	0
Flexible A[a] (samples 5–15)	5.1 ± 2.6		5.70 ± 4.1	9.2 ± 9.0	76.1 ± 32.6	14.7 ± 2.7
Flexible B[b] (samples 16–23)	1.9 ± 1.6	0.10 ± 0.03 0.09 ± 0.06	59.1 ± 37.4	82.5 ± 9.2	15.2 ± 7.1	2.3 ± 0.5

[a] Low Al content.
[b] High Al content.