ENERGY UTILIZATION OF BY-PRODUCTS FROM MECHANICAL RECYCLING PROCESS OF ELECTRONIC WASTE

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Abstract

The article deals with energy utilization of by-products from the mechanical recycling of electrical and electronic equipment. This is essentially crushed mixed plastic and dust from dust removal and filtration process. Final products of this technology are primarily metal parts, other by-products are landfilled. Individual samples are analysed for fuel properties and are determined element analyses and defined stoichiometric models of combustion.

The values of elemental composition show a high proportion of non-combustible particles that reach up to 77%. Mixed plastic is only material which can be used without major modifications (under 0.7 mm) and has 34% of ash with calorific value of 22.39 MJ.kg^{-1}. The values of stoichiometric calculations indicate different parameters of supplied combustion air amount, amount of flue gas and combustion temperatures. These differences are based primarily on total amount of carbon and hydrogen in the elemental composition of the original samples and the differences are also recorded in the graphic dependency of CO_2 on oxygen content in exhaust gas.

Key words: calorific value, combustion temperature, carbon dioxide, excess air coefficient, ash.

INTRODUCTION

Production of electrical and electronic equipment is the fastest growing sector of industrial development. Handling and processing of electronic waste (e-waste) will continue to be a topic of interest in the future (WIDMER ET AL., 2005; CUI, FORSSBERG, 2009). High diversity in the composition of e-waste is the result of fast technological progress in the electronics industry, which introduces difficulties for the development of universal, sustainable recycling processes (HILTY, 2005; BAZARGAN ET AL., 2012). The effects of various organic and metal components of electronic waste on human health and the environment are summarized based on the available knowledge in (WONG ET AL., 2007; DIMITRAKAKIS ET AL., 2009). A negative effect on the environment and health caused by electronic waste is increasingly important. E-wastes are made up of different organic substances and metals in a polymer matrix. Organic substances, particularly fire retardants and other additives are potential carcinogens (NNOROM&OSIBANJO, 2009). Toxic heavy metals such as cadmium, chromium, mercury and lead are released into the environment, mainly through electronic waste leaching and incineration. These metals are highly toxic and represent a high risk to human health and are a major negative influence on the environment (WONG ET AL., 2007; DIMITRAKAKIS ET AL., 2009).

Among methods for recycling of electronic waste there are chemical processes: pyrolysis, gasification, depolymerization and hydrogenolytic degradation to obtain chemical raw materials or fuels or currently perspective mechanical processing (GUO ET AL., 2009). Some experience in the pyrolysis and combustion processing of printed circuit boards in a horizontal combustion unit to determine the level of pollutant gaseous substances are described by MOLTÓ ET AL. (2009) at temperature 500°°C and MOLTÓ ET AL. (2011) at temperatures around 850°°C. Kinetic study of mobile phone thermal decomposition was carried out under variousthermogravimetric measurements at temperature 500°°C in study FONT ET AL. (2011). More than 50 compounds, including carbon oxides, light hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) were identified and quantified.

The aim of the article is not research of the main products of recycling technology. The article deals with by-products from recycling line for e-waste, for which there is no further use and therefore are landfilled. New legislative requirements for waste treatment strictly recommend energy utilization before landfilling. Therefore this article deals with the energy use of by-products for combustion with regard to their combustion characteristics and emission production. The contribution of the article is the analysis of by-

products from mechanical processing of electronic waste which are intended for energy use. The materials are plastics sized up to 1.5 mm, dust captured from the cyclone and dust from the filter.

MATERIALS AND METHODS

Sampling is carried out on a line for processing e-waste by physical methods. Incoming material is mainly from offices and collective collection of e-waste. Hazardous substances are first sorted out from the e-waste at the input to the line. Subsequently twin-shaft shredder coarsely crushes and a single shaft grinder finely grinds this material. Crushed and ground material is led by air into cyclone separators where a dust fraction is separated and the finest particles end in a dust filter. Material for separation proceeds to a buffer container and from there by vibratory conveyor is led to a fluidized bed sluice. On the separation area of the fluidized bed sluice separation occurs due to vibrations and material suspension by air stream. Input material into several product groups according to their specific weight, e.g. pertinax (PCB?) and metals separation. By-products from fluidized bed sluice are collected into separate containers.

The following material fractions were captured: I. mixed plastic from fluidized bed sluice (1.5 to 0.7 mm), II. mixed plastic from fluidized bed sluice (below 0.7 mm), III. dust from cyclone and IV. dust from filter. The proportion of these individual fractions in the line consists of: about 6.2% wt. for I. mixed plastic, about 2.3% wt. for II. mixed plastic, about 2.5% wt. for dust from cyclone and about 3% wt. for dust from filter.

Determination of water and ash contents is done according to CSN Solid recovered fuels - Determination of ash content using a thermogravimetric analyzer (EN 15403). Determination of sulfur (S), hydrogen (H), carbon (C) is measured by infrared spectroscopy (analyzer CHN+S) and the emission factor by calculation. Determination of nitrogen (N) by thermal conductivity detection in a CHN analyzer. Determination of chloride concentration after combustion is determined spectrophotometrically according to CSN Stationary sources of emissions - Determination of mass concentration of gaseous chlorides expressed as HCl - Standard reference method (CSN EN 1911). Determination of gross calorific value is determined by the calorimetric method in an isoperibolic calorimeter and heating value by calculation using standard Solid recovered fuels - Determination of gross calorific value and heating value (CSN EN 15400).

Individual samples were analysed by stoichiometric calculations. During this analysis real molar volumes of gas were used values to calculate the theoretical dependence of the emission concentration amounts of CO_2 on the excess air coefficient n.

The theoretical amount of emission concentrations of CO_2 (m^3.kg^{-1}) is based on the equation:

$$CO_2 = \frac{\frac{22,27}{12,01} \cdot C}{v^s_{sp\,min}} \cdot 100 \qquad (1)$$

The theoretical amount of dry flue gases (m^3.kg^{-1}) is based on the equation:

$$v^s_{sp\,min} = \frac{22,27}{12,01} \cdot C + \frac{21,89}{32,06} \cdot S + \frac{22,40}{28,013} \cdot N + 0,7805 \cdot L \qquad (2)$$

Where the theoretical amount of dry air L (m^3.kg^{-1}) is determined from the equation:

$$L = O_{min} \cdot \frac{100}{21} \qquad (3)$$

The theoretical amount of oxygen O_{min} (m^3.kg^{-1}) is based on the equation:

$$O_{min} = \frac{22.39}{12.01} \cdot C + \frac{22.39}{4.032} \cdot H + \frac{22.39}{32.06} \cdot S - \frac{22.39}{31.99} \cdot O \qquad (4)$$

Where C, H, S and O are contents of carbon, hydrogen, sulfur and oxygen in the fuel sample (% wt.).

Adiabatic combustion temperature t_a (°C) is determined for further evaluation of the samples. This temperature characterizes a fuel's adiabatic combustion conditions and determines the conditions of complete combustion when $n = 1$. The adiabatic temperature of combustion is expressed by the equation:

$$t_a = \frac{Q_n}{v^s_{sp\,min} \cdot c_{sp}} \qquad (5)$$

Where $v^s_{sp,\,min}$ is the volume of flue gas when n = 1 (m^3.kg^{-1}) and c_{sp} is the specific heat capacity of flue gas (kJ.m^{-3}.K^{-1}).

The theoretical combustion temperature t_t (°C) is used as a reference for different fuels at different or the same conditions of the combustion process. This temperature allows to change the values of combustion air consumption ($n \geq 1$), fuel enthalpy value ($Q_p \geq 0$) and air specific enthalpy ($Q_{vz} \geq 0$) and is determined from the equation:

$$t_t = \frac{Q_n + Q_p + Q_{vz}}{v^s_{sp\,min} \cdot c_{sp}} \qquad (6)$$

RESULTS AND DISCUSSION

The average values of elemental composition most important for fuel utilization are shown in Tab. 1. The limiting factor for direct combustion is the concentration of combustible and non-combustible components in the samples. Most limiting for chosen samples is the measured high concentration of ash. Especially in samples of mixed plastic in size of 1.5 to 0.7 mm, samples from the cyclone and the dust filter deter-mined ash content has gone above the limit amount. The amount of ash significantly affects the fuel properties of assessed solid samples and consequently affects both the selection and the setting of combustion device as indicated by MALAŤÁK ET AL. (2015). Similar results of mineral composition of raw input material have been achieved by MOLTÓ ET AL. (2009).

Tab. 1. – The final values of elemental analysis

Sample / Average values	Water Content (% wt.)	Ash (% wt.)	Gross Calorific Value (MJ/kg)	Net Calorific Value (MJ/kg)	Carbon C (% wt.)	Hydrogen H (% wt.)	Nitrogen N (% wt.)	Sulphur S (% wt.)	Oxygen O (% wt.)	Chlorine (% wt.)
	W	A	Q_s	Q_i	C	H	N	S	O	Cl
I. original sample	0.84	**33.74**	22.39	21.76	41.56	5.27	0.01	0.17	18.2	1.89
I. dry sample	-	**34.02**	23.12	21.96	41.92	5.31	0.01	0.17	18.34	-
II. original sample	0.49	11.85	**31.49**	29.86	63.23	**7.42**	0.01	0.11	15.90	**2.84**
II. dry sample	-	11.91	**31.65**	30.02	63.54	**7.46**	0.01	0.11	15.97	-
III. original sample	0.99	**76.70**	**6.26**	**5.89**	**13.70**	1.58	> 0.01	0.15	5.90	0.391
III. dry sample	-	**77.46**	**6.32**	**5.97**	**13.87**	1.60	> 0.01	0.15	5.96	-
IV. original sample	0.78	**75.04**	**6.98**	**6.58**	**15.91**	1.73	>0.01	0.09	5.40	0.337
IV. dry sample	-	**75.63**	**7.03**	**6.65**	**16.03**	1.74	> 0.01	0.09	5.44	-

Large amounts of ash influenced mainly the calorific value of samples and thus percentage of combustible elements. Highest calorific value was achieved in the sample of mixed plastic in the size under 0.7 mm as shown in Tab. 1 while the sample also reached the highest hydrogen concentration.

Significant quantities of chlorine have been found mainly in samples of mixed plastic. The negative influence of chlorine is based on two effects of HCl emissions. First, it may affect the formation of poly-chlorinated dibenzo / dioxins and furans (PCDD / F) and there are also the corrosive effects of HCl and its derived compounds (LAUNHARDT ET AL., 1998).

The values of stoichiometric calculations (Tab. 2) show various flue gas parameters of examined samples converted to normal conditions, dry flue gas and to $n = 1$. Stoichiometry shows how parameters of calorific value, ash content and energy density affect selection or design of the combustion device and setting for optimum combustion. Concentration particularly of ash, hydrogen, oxygen and chlorine in the assessed samples are varying relatively widely. This fact is confirmed also by performed flue gas analyses.

**Tab. 2.** – Theoretical flue gas values from stoichiometric calculations

Sample / Average values	Theoretical amount of air		Theoretical amount of dry flue gases		Theoretical concentration of carbon dioxide in dry flue gases	
	$kg.kg^{-1}$	$m^3.kg^{-1}$	$kg.kg^{-1}$	$m^3.kg^{-1}$	% wt.	% vol.
I. original sample	5.82	4.48	7.92	4.27	19.24	18.04
II. original sample	9.15	7.05	11.23	6.68	20.64	17.54
III. original sample	1.87	1.44	3.93	3.03	12.79	18.29
IV. original sample	2.20	1.69	4.25	1.62	13.72	18.16

I. original sample
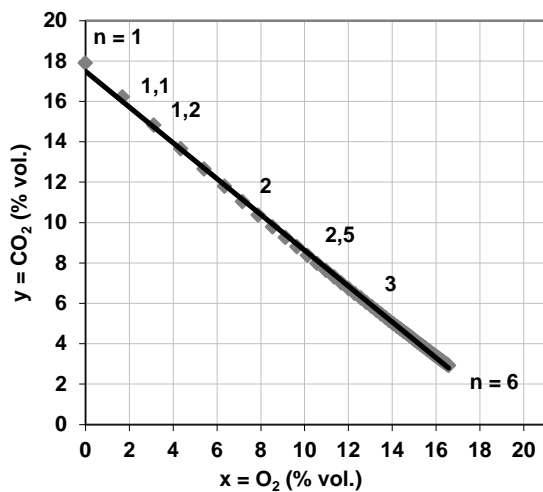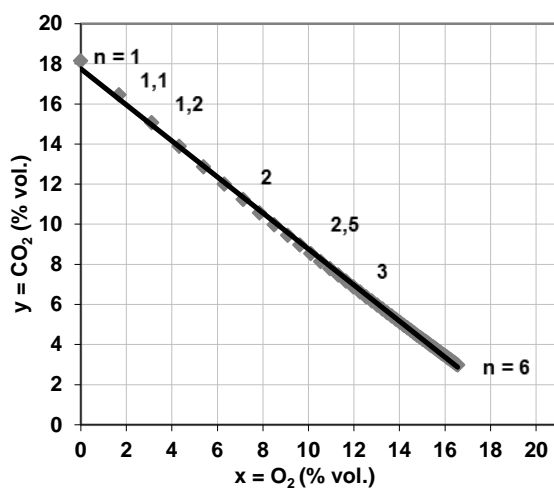

$$y = -0.8861x + 17.482$$

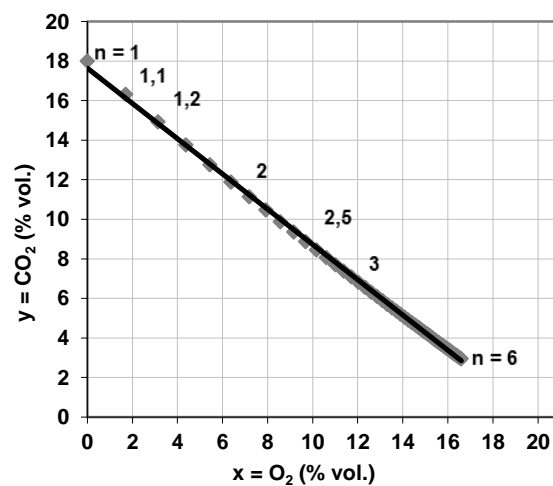**II. original sample**
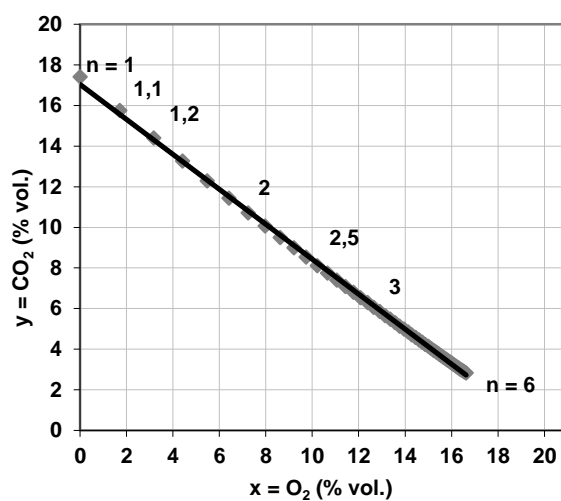
$$y = -0.8614x + 17.041$$

III. original sample

$$y = -0.8987x + 17.742$$

IV. original sample

$$y = -0.8918x + 17.64$$

Fig. 1. – Dependence of CO_2 emission concentration on the oxygen content O_2 in the flue gas with the expression of the excess air coefficient n

For each sample a graph of dependence of the carbon combustion to carbon dioxide on the oxygen content in the flue gas (Fig. 1) is shown. For these dependencies a linear regression equation was fitted. The trends are influenced by the amount of carbon and the share of other elements in the fuel and thus by the maximum

concentration of carbon dioxide in the flue gas (see Tab. 2). Similar results were achieved by MALAŤÁK ET AL. (2008); WEI ET AL. (2012); MALAŤÁK & BRADNA (2014).

No less important parameter for comparison of samples is the adiabatic combustion temperature t_a (°C). This is determined for I. sample of mixed plastic (1.5 to 0.7 mm) t_a =2808 °C, for II. sample of mixed plastic (under 0.7 mm) t_a =2560 °C, for III. sample of dust from the cyclone t_a =2446 °C and for IV. sample of dust from the filter t_a =2350 °C. The theoretical com-

bustion temperature t_t (°C) is used for comparison of samples at the same conditions of the combustion process in dependence on excess air coefficient n. LIU ET AL. (2013); LOU ET AL. (2016) confirm that the concentration of nitrogen oxides depends both on combustion temperatures above 1000 °C, but also on the amount of supplied air, which is expressed by excess air coefficient, which is mentioned in the literature by value about 2–3 (CHAIKLANGMUANG ET AL., 2002; MALAŤÁK ET AL., 2008; HOUSHFAR ET AL., 2011).
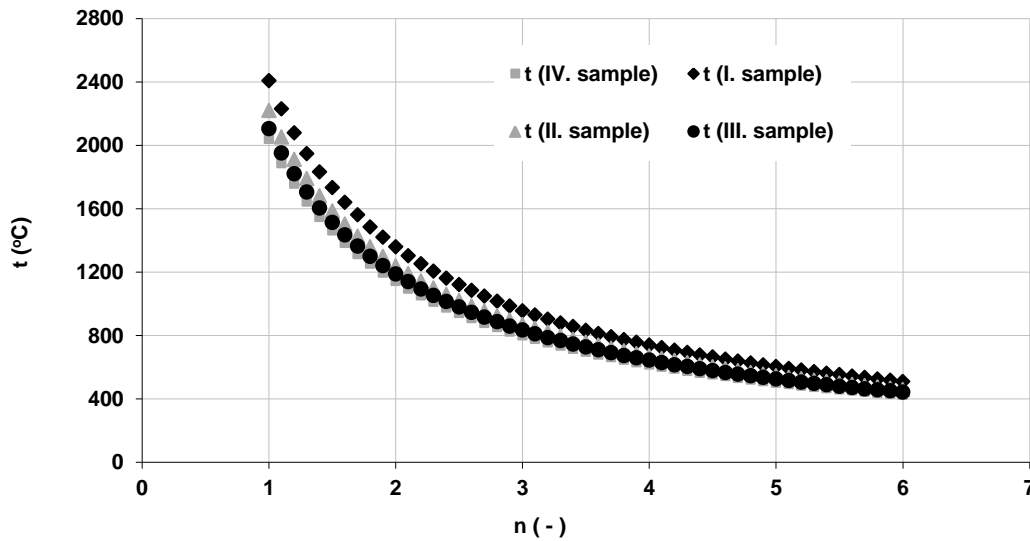

Fig. 2. – Theoretical combustion temperature t_t of individual original samples depending on the excess air coefficient n

CONCLUSIONS

Samples of mixed plastic I. (under 0.7 mm) have a high calorific value and a reasonable amount of non-combustible matter. These samples may serve as an alternative fuel that is equal to the quality of coal. Unfortunately the size of these samples under 0.7 does not allow direct combustion in conventional boilers, but is possible for example in a fluidised combustion device. Another possibility is pyrolysis processing.

High portion of non-combustible matter of 34% wt. in samples of mixed plastic (1.5 to 0.7 mm) rather restricts its other direct energy utilization. Therefore it is necessary to modify this material by reduction of the ash concentration to the allowable amount by mixing with other energetic material (e.g. biomass). Such modified fuel can be used in combustion devices

where the intended fuel has similar properties. There is also the possibility of co-combustion with other energetic material or new design of specific combustion device.

The other, very problematic, samples from the process of e-waste recycling are those from the cyclone and the dust filter with a high percentage of non-combustible matter above 75%. This material is finally evaluated as energetically negative and cannot be used without substantial modification for energy purposes. Another issue is the actual elemental composition of ash, which contains some risky elements such as lead, mercury and PAHs coming from the e-waste. These risk characteristics are also monitored, but not discussed in this article.

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