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Short Communication

Energy Recovery from Waste of Printed Circuit Boards in Plasmatron Plasma Reactor

Jakub Szałatkiewicz*

Industrial Research Institute for Automation and Measurements, PIAP
Al. Jerozolimskie 202, 02-486 Warszawa, Poland

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Abstract

This paper presents results of research on the use of plasma technology for printed circuit boards (PCB) processing for metals and energy recovery. In the Industrial Research Institute for Automation and Measurements, a test stand was built allowing experiments on plasma process with throughput of 800 kg per day. Brief examination of PCB waste was carried out, focusing on identification of its heating value and composition of organic substances including C, H, O, S, and Br. Heat balance of the process is presented, including energy supplied by plasma, chemical energy released by incineration of PCB waste, heat carried out with molten metal and slag, heat carried out with exhaust fumes, and heat losses of the apparatus. Also, the incineration process is described focusing on air demand and its efficiency due to incomplete burning of the organic substances in the reactor. The presented process in total consumes 66 kW of electrical energy, and allows recovery of 117 kW of heat energy from exhaust fumes.

Keywords: PCB, printed circuit boards, WEEE, waste, recovery, plasma, energy

Introduction

Increasing digitalization of appliances and machines equips them with electronic and electric printed circuit boards (PCBs). After the end of an appliance's life, it becomes hazardous waste that needs to be handled adequately. On the other hand, mass production of electric and electronic equipment requires large amounts of non-renewable resources, including precious metals. The amount of WEEE increases continuously and WEEE has to be utilized, but it also can become a source of valuable resources. That is why it is essential to develop new effective technologies for recovering metals and energy from this specific waste.

Apart from significant amounts of metals available for recovery, the waste of printed circuit boards also contains a considerable amount of chemical energy that can be recovered. Currently, this resource is sold to smelting plants for recovery of metals outside Poland. The plasma technology presented in this paper can become an attractive alternative for currently used large-scale smelting technologies, and allows recovery of metals and energy from this special waste.

Combustibility of Printed Circuit Board Waste

PCB waste contains three main groups of substances: metals, non-metals, and organic compounds. Each of these groups covers approximately 33% of its mass [1]. Organic substances in PCBs, are mainly epoxy resin in board laminate and other elements that contain atoms of carbon (C), hydrogen (H), oxygen (O), bromine (Br), and chlorine (Cl) (i.e. paint, rubber, PVC insulation). PCB laminate – epoxy resin reinforced with ceramic fibers – is also filled with brominated fire retardants to decrease its flammability and increase temperature resistance. Widely used for this pur-

*e-mail: jakub.szalatkiewicz@gmail.com
jszalatkiewicz@piap.pl

Table 1. Elemental analysis of organic elements in PCB waste [2, 3, 7].

	Mass composition of organic elements in PCBs (%)						
	C	H	N	S	O	Br	Other
PCB 1	26.36	2.8	1	0.02	15.58	6.5	n/d
PCB 2	18.10	1.8	0.32	n/d	6.03 (org)	5.07	0.45 (Sb)
PCB 3	24.69	1.38	0.85	1.97	n/d	4.94	2.05 (Cl)
PCB 4	24.90	2.7	0.25	n/d	2.63	4.89	n/d
	Average						
Average	23.51	2.17	0.6	1 (0.21)	8 (4.33)	5.35	n/d

pose is TBBPA (Tetrabromobisphenol A) and Sb due to its additional effectiveness in reducing flammability [2].

Literature data indicate that the heating value of PCB waste is 9.72-11.37 MJ/kg [3, 4]. In order to verify this data, the heating value was calculated using equation (1) [5] for averaged composition of elements C, H, S, and O presented in Table 1, found in this waste.

Data of waste composition presented in Table 1 is strongly variable, particularly the O and S contents are out of range, so further calculations of S content will be used based on author own research of electronic PCB samples that contained 0.21% of sulfur. As for oxygen composition, 15.58% value was excluded due to excessively increasing its average composition. Also, humidity in calculation of waste heating value was assumed to be 0%.

$$W_d = 32800C + 120040\left(H - \frac{O}{8}\right) + 9260S \quad \left[\frac{\text{kJ}}{\text{kg}}\text{fuel}\right] \tag{1}$$

The calculated heating value for averaged C, H, O, and S elements equals 9.7 MJ/kg, which is similar to literature data.

Experimental Setup

In 2010 a research project was undertaken to investigate and design plasma-based technology allowing processing of waste of PCBs and the recovery of metals they contain. In the Industrial Research Institute for Automation and Measurements, the experimental setup was designed and tested. The test stand is presented in Fig. 1. The key component of the experimental setup is the plasma reactor, equipped with three plasmatrons – plasma sources located at every 120º around the reactor chamber circumference. The test position is equipped with peripheral systems, measurement and control apparatus for data acquisition and control of the process during research. The developed test stand allows a wide range of experiments and data acquisition during research on waste processing, and recovery of metals and energy. The block diagram of our laboratory setup is presented in Fig. 2.

Prepared waste portion is transported through an automatic feeder to the plasma reactor chamber. In the reactor chamber, the waste is incinerated and melted by three plasma streams. Next, the fumes are transported to the scrubber where they are neutralized, cooled, and released to the atmosphere. Metals and slag in molten form flow out from the reactor and solidify in moulds, from which they can be recovered and recycled.

Incineration Process in Plasmatron Plasma Reactor

In the plasma reactor under the conditions of high temperature and plasma streams, incineration and melting of waste is carried out. The plasmatron plasma reactor is equipped with three sources of heat, which are 20 kW arc plasmatrons. Each plasmatron generates the stream of plasma that flows out at the bottom of the reactor chamber. The plasma is produced from compressed air, which is used as plasmatron working gas. Fig. 3 presents a working plasmatron and generated plasma stream. PCB waste contains in its mass approximately 33% of organic substance, which requires certain oxygen mass for its complete incineration. Plasmatrons deliver 11 Nm^3/h of air in the form of ionized plasma, but it is possible to supply the reactor with additional compressed air for incineration. Based on the equa-

Fig. 1. Overview of the laboratory setup: 1) plasma reactor, 2) plasmatron, 3) molten product collection, 4) fume exhaust – chimney, 5) waste package transporter, 6) plasmatron power supply, 7) PLC – automation and data collection apparatus cabinet, 8) automatic waste package feeder.

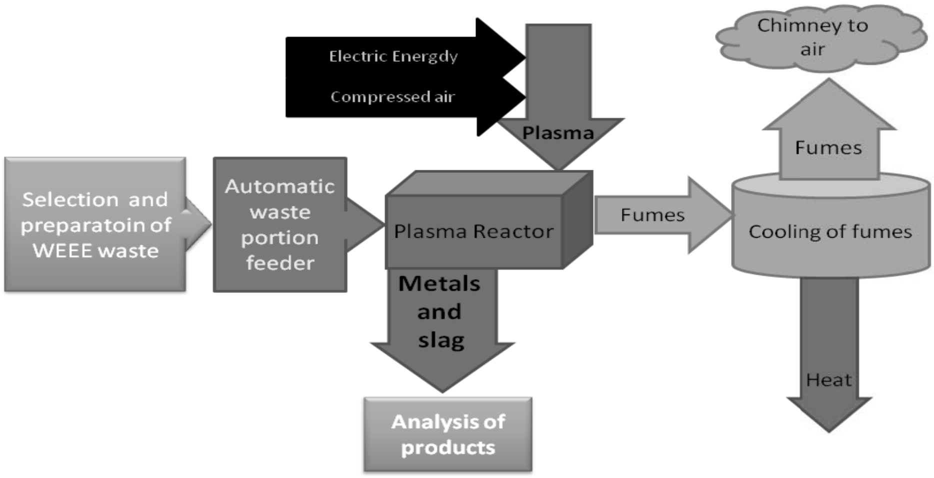

Fig. 2. Block diagram of the designed process for research on high-temperature plasma technology for metals recovery and waste neutralization.

tion (2) [6] and waste composition (Table 1), the required volume of air was calculated for stoichiometric incineration of 1 kg PCB waste.

$$L_0 = 3.336\left(\frac{8}{3}C + 8H - O + S\right) \left[\frac{\mathrm{Nm}^3}{\mathrm{kg}}\,\mathrm{fuel}\right] \quad (2)$$

The calculated stoichiometric volume of air for incineration of 1 kg of waste is 2.6 Nm³/kg.

In experiments 1 kg waste portion was introduced each minute to the reactor chamber. The air provided by the plasmatrons is 0.18 Nm³/minute, meaning that only 7% of the required air for incineration is provided. Additional air was blown in (14 Nm³/h), resulting in a total of 25 Nm³/h, which allowed covering 16% of total air demand for incineration of 1 kg of waste per minute. This means that it is impossible to fully incinerate such an amount of waste in such a short period of time, and only 9.6 kg/h of waste can be incinerated completely. Also, it is important to notice that next to organic substances being incinerated, metals also become oxidized due to high temperature and plasma presence. Oxidation of metals increases the amount of energy in the reactor but also consumes oxygen and decreases the mass of recovered metals.

One solution for the insufficient amount of air for incineration is to decrease the mass of waste portion. Calculating the required amount of air for incineration of 0.5 kg waste portion in the reactor, the available amount of air (25 Nm³/h) covers 32% of required amount of air for the steichometric incineration process, and in the case of 0.25 kg waste portion, available air suffices for 64%. This means that available air amount is not sufficient for such high waste processing rate in given process conditions. Moreover, decreasing waste portion mass affects technology throughput, increasing the time of processing each portion of waste, which affects process economy and energy consumption. The solution for this issue is to equip the developed reactor with an additional afterburner chamber in which the gaseous products from plasma reactor will be fully incinerated. Such a solution will allow processing of PCB waste, smelting the metals from it, and recovery of all energy that is available in the processed waste.

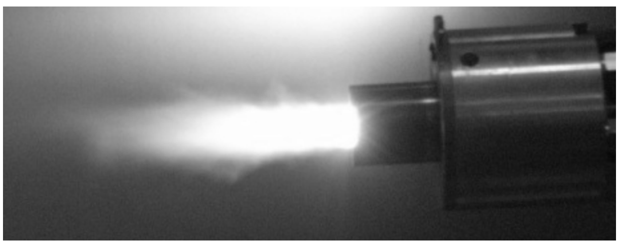

Fig. 3. Generated plasma stream by plasmatron.

The incineration process in plasmatron plasma reactor is monitored by a wideband lambda sensor, allowing measurement of oxygen in the fumes. Exemplary oxygen concentration graph is presented in Fig. 4, where within the proximity of 16 s a sudden drop of oxygen is visible, which indicates that the waste portion was introduced to the reactor. Next, the oxygen concentration rises and reaches the air level after about 214 s. At the end of the graph another sudden drop of O_2 concentration is present due to another waste portion feeding.

During experiments using 11 Nm³/h of air, and processing of printed circuit boards, exhaust gas samples were collected and analyzed. Analysis results are presented in Table 2. In the analyzed gas sample also heating value and density was calculated, which can be utilized for design of the afterburner chamber. Data presented in Table 2 confirms that only partial waste incineration process occurs in current construction of plasma reactor.

Heat Balance of Plasma Reactor for Processing of Printed Circuit Boards

Heat balance of the plasma process is described by equation (3), where the right-hand side of the equation presents sources of heat, and the left-hand side of the equation heat outflows.

Table 2. Composition of sample exhaust fume samples collected during experiments from plasma reactor processing PCB waste.

Molecule	% v/v
H_2	10.36
O_2	1.57
N_2	62.61
CO	15.37
CH_4	0.16
CO_2	7.49
C_2H_4	0.06
COS	<0.0005
Benzene	0.039
Heating value	3.23 MJ/m³
Density	1.184 kg/m³

$$Q_{fumes} + Q_{loss} + Q_{solids} = Q_{plasma} + Q_{incineration} \quad (3)$$

...where:

Q_{fumes} – Heat carried away with exhaust fumes from the reactor, this heat is available for recovery and utilization. Temperature of the fumes exiting the reactor chamber is 1,400ºC.

Q_{loss} – Heat loss due to conduction through reactor walls to the surroundings. Calculated based on conductivity of used materials, reactor construction, and recorded temperatures. Heat loss during normal operation of the reactor at 1,550ºC is 5 kW. Heat loss in heat balance during 1 hour operation: 5 kWh = 18 MJ.

Q_{solids} – Heat carried away from the process with molten metal and slag. This heat is calculated based on the solid products mass, composition, specific heat and heat of fusion for each element. Depending on processed waste composition, mass of metals and slag reaches from 60 to 80% of the input waste mass. Heat carried out with solids is treated as waste due to its small amount. Each kg of molten solids carries 1.28 MJ/kg of heat from the reactor. In heat balance, the assumed mass of solids produced from the processed waste is 68%, and mass of processed PCB waste is 30 kg/h, so heat carried with solids equals 26.1 MJ.

Q_{plasma} – Heat supplied to the reactor by three plasmatrons, in the form of ionized air. Heat is calculated based on energy balance and energy efficiency of plasmatrons. In experiments, the amount of heat supplied by three plasmatrons equals 48 kW. In heat balance, during 1 hour of operation, plasmatrons delivered 172 MJ of heat (48 kWh).

$Q_{incineration}$ – Heat produced by incineration of organic substances present in processed PCB waste. Heating value of PCB waste is 9.7 MJ/kg, and during an hour of operation 30 kg of waste was processed, releasing in total 292 MJ of heat.

Heat energy available for recovery from exhaust fumes can be calculated from rearranged equation (3) to the form of equation (4):

$$Q_{fumes} = Q_{plasma} + Q_{incineration} - Q_{loss} - Q_{solids} \quad (4)$$

Assuming stable and constant operation parameters of the process, and complete combustion of 30 kg/h of printed circuit boards the heat balance will result in Q_{fumes} = 421 MJ/h = 117 kWh.

Calculated heat balance reveals that energy supplied for the reactor in the form of plasma provides only 37% of total process heat. Remaining heat is generated by incineration of organic substance in processed waste. Moreover, heat energy available for recovery from exhaust fumes accounts for 117 kW. Heat loss of the process accounts for 9.4% and also can be indirectly utilized for heating of the surroundings. This means that for every 1 kW of electrical energy used in the process, 2 kW of heat will be available for recovery.

Conclusions

Presented calculation and heat balance show that the examined plasma process for recovery of metals and energy from PCB waste consumed in total 66 kW and processed 30 kg/h of waste, allowing for the recovery of 117 kW of

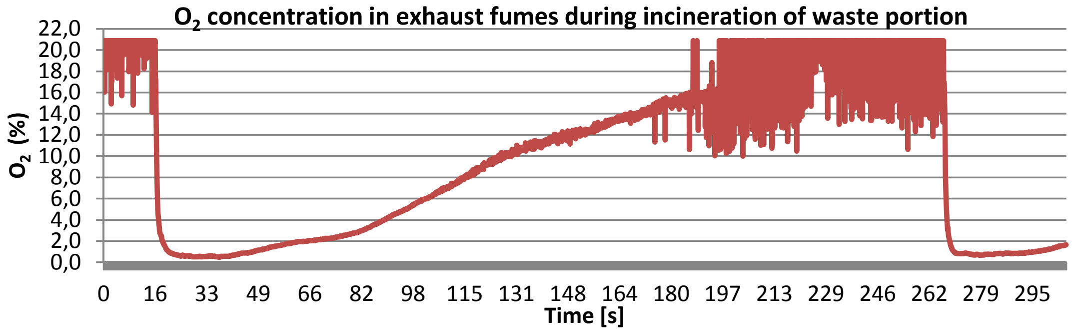

Fig. 4. Example of oxygen concentration in exhaust fume graph recorded during experiments.

heat from exhaust fumes. Their temperature is 1,400ºC, and is sufficient for efficient heat recovery and its utilization. The presented investigation was carried out on research test stand, which allows experiments with throughput of 30 kg/h and more of waste. Processing of waste of printed circuit boards in this plasma technology consumes 2 kWh/kg, allowing recovery of metals and energy.

The presented heat balance shows that plasma energy used in the process accounts for 37% of total process; energy, therefore increasing the scale and throughput of the process; energy recovery generated by incineration of waste will increase twice as fast as electrical energy.

Current construction of the designed test stand does not allow for complete incineration of organic substances present in PCB waste, thus for correct operation of such installation it is necessary to equip it with an afterburner chamber. In such chamber, products of incomplete incineration exiting plasma reactor will become completely burned, therefore additional energy will be released and emission in exhaust fumes will decrease.

Further optimization of the developed process is carried out with a focus on reduction of energy demand of the process, increase of the throughput, maximization of metals recovery in metallic form, and meeting emission standards for such installations.

Designed plasma technology for processing of printed circuit board waste allowing recovery of metals and energy can be applied in WEEE processing plants [8], in which next to disassembly of WEEE, segregated PCBs will be immediately processed. Such an option for processing of segregated waste from WEEE is a valuable asset of this technology, allowing simultaneous recovery of metals, neutralization of waste, and energy recovery that is able to cover the energy demand of such a facility.

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