Dynamics of the combustion process of printed circuit boards inside a fluidized bed reactor

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Keywords
WEEE – printed circuit board – fluidized bed reactor

Abstract

The following article presents the method for thermal transformation of printed circuit board (PCB) components mostly from a PC main board. The combustion process was carried out inside a laboratory scale fluidized bed reactor. During the process the concentration of gases such as NO\textsubscript{x}, CO, CO\textsubscript{2}, SO\textsubscript{2} in exhaust fumes was continuously measured. Furthermore, the dynamics of each part of the PCB has been studied.

1. Introduction

Currently we can observe a global steadily increasing amount of electrical and electronic waste. This is mostly connected with the technological progress and the desire to own the latest equipment and devices. Considering this waste as ordinary communal waste and leaving them in landfills is a growing problem. Used electrical and electronic equipment left unprocessed has an adverse effect both on human health and environment. This results from the fact that such equipment contains a number of metals (including heavy metals) and organic compounds that can permanently pollute the environment. Due to the various composition of such equipment electrical and electronic waste should be gathered, sorted and utilization. This is becoming a growing necessity [4]. It is estimated that in the European Union 10,3 Tg of new electrical and electronic equipment is introduced annually. Also it is estimated that by the year 2020 the combined amount of waste coming from used up electrical and electronic devices will reach approx. 12,3 Tg [7].

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Waste electrical and electronic (WEEE) contains elements that are relatively easy to separate mechanically such as casings, steel construction elements etc. however, currently the design of such devices is more and more complicated as virtually every single such device contains a printed circuit board (PCB). Integrated electronic circuits are composite objects in which every element is firmly connected with other elements, which ensures reliability of such a circuit. This is mostly the case with household appliances – more of them are considered digital devices. Disassembly of each element of a circuit board consumes a lot of energy and labour and does not yield recyclable elements. The PCB itself (also called a laminate) is a board made of insulating materials (plastics bound by a non-organic filling) containing electrical connections (conductive traces) and soldering points (connection pads). Materials commonly used to manufacture PCBs are: epoxy resin pre-preg, epoxy resin laminate, composite materials including layers of paper or glass felt. Components found in PCBs i.e. the functional electronic elements can be made of different materials, metals, semi-conductors, plastics [8].

The basic in the European Union regulating waste management systems, electrical and electronic equipment is Directive 2002/96/EC of the European Parliament and the Council of 27 January 2003. It's main goal is to reduce the amount of WEEE and re-usage and recycling of such equipment in order to reduce waste. In European Union countries had been imposed the duty to design and manufacture of electrical and electronic equipment in a way that facilitates dismantling and recovery. These activities were also supported by the guidelines of the Directive 2002/95/EC of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment [7].

Directive 2002/96/EC indicated for each group of electrical and electronic waste the required minimum levels of recovery and minimum levels of reuse and recycling. Depending on the group of waste electrical and electronic equipment minimum required level of recycling was set at 50 – 75%, and for the recovery of 70 – 80%. In terms of recovery and recycling in Poland in 2008 the required levels have been reached, with the exception of large stationary industrial equipment. However, already in 2009 obtained the required levels of recovery and recycling of waste for all groups of electrical and electronic equipment [11].

According to the said Directive countries of the European Union are required to collect at least 4 kg of waste electrical and electronic equipment from private households per inhabitant per year. The requirement should be meet in 2008. However, Poland still has not managed to fulfill this [11]. In many European countries this was achieved as early as 2008. The best results have been achieved in Sweden (14.8 kg), Denmark (13.9 kg), Ireland and Austria (around 9 kg) [10].

WEEE incineration reduces the amount of environmentally harmful waste and allows obtaining energy stored in chemical bonds of combustible ingredients in a useful form, which could allow the process to become autothermic. Incineration also allows the application of simple methods of recovery of useful metals.

Currently in the European Union only approx. 12% of dangerous waste is incinerated (22 Tg of harmful waste is generated).

In 2010 12 Polish construction projects of waste incineration plants were reported. Today, however, four metropolitan areas gave up the idea of constructing modern energy recovering plants or have lost a chance for the EU grants. For example, plans for an incineration plant in Olsztyn were cancelled and a plant for mechanical-biological waste treatment was built [3]. The European Union has approximately 370 waste incineration plants in operation but Poland has only a one small such plant. It is a waste incineration plant with a capacity of about 40 000 Mg/p.a.: the sorting and composting plant next to one of the processing plants for waste disposal plant in Warsaw's ZUSOK operating since 2001 [13].
2. The experiment

The following experiment involved thermal transformation of PCB elements in a laboratory grade fluidized bubbly bed reactor. Thermal treatment consisted of incineration in very good heat exchange conditions inside the fluidized bed. A mixture of air and propane-butane was used to reach the required temperature. We focused on presenting the dynamics of process and fumes’ emission from each part of the PCB.

2.1 Research station

The thermal process was carried out in a fluidized bed reactor with a chemically inert bed. Such a bed has an even temperature spread, has a high temperature and a large turbulence of the solid and gaseous state, which is required to have adequate access to oxidizing agent necessary to burn out all the combustible substances (mainly in the polymer part) from electronic waste.

The side of the reactor is a quartz pipe 96 mm in diameter and 400 mm high. It is installed on a flat chromium and nickel distributor 1 mm thick. The distributor has evenly places openings through which air and propane-butane are introduces into the reactor. The system for temperature control is a moving thermal shield and a cool air blower. Additionally we used a heat-proof wire mesh basked to place the studied the samples into the bed and to take out the non-combustible remains.

The characteristic of the combustion process was done through the analysis of exhaust gases and measuring temperature inside the fluidized bed. The exhaust gases were gather using a heated probe above the bed and they were directed to the analyzing devices. To measure the temperature two thermocouples placed 20 mm and 50 mm above the basket’s bottom, which was placed inside the fluidized layer.

The same research station was used earlier to research chosen aspects of fuel combustion kinetics [1, 2, 15, 19] and ecological aspects of waste incineration [9, 12, 15, 17]. The station’s diagram can be seen in figure 1.
2.2 Description of the experiment and analysis of its results

The incineration of PCB fragments was performed in a laboratory grade reactor with a hot sandy fluidized bed. The sand used had grain size 0.43 – 0.50 mm and its mass was 400 g. The fuel required to reach a steady and high temperature was propane-butane. Solid fuels were parts of a PCB from a computer. The fragments were made by manual disassembly.
Afterwards the fragments were chopped using a guillotine into smaller bits with mass from 2.37 to 9.81 g. Figure 2 is a picture shows the PCB before and after breaking it into smaller pieces. Specific parts used in the experiments are marked.

Figure 2. A printed circuit board before and after disassembly and slicing.

Rysunek 2. Obwód drukowany przed i po demontażu mechanicznym oraz pocięciu.

For the experiment 4 characteristic samples were used from a pool of 31. The 4 ones were very different in terms of mass and electronic parts. Table 1 show the properties of the parts used in the incineration process.

Table 1. Physical properties of the chosen PCB elements.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
<th>Sample D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminate</td>
<td>2.910</td>
<td>8.655</td>
<td>2.494</td>
<td>4.015</td>
</tr>
<tr>
<td>Integrated circuit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolytic capacitor</td>
<td>0.38</td>
<td>0.80</td>
<td>0.67</td>
<td>1.15</td>
</tr>
<tr>
<td>Large plastic elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each sample was introduced into the reactor using a basket made of heat-resistant wire mesh. Incineration time for each element was 3 minutes. Afterwards the basket containing the non-combustible parts was pulled out. As it turned out these parts were fragile. During the incineration the exhaust fumes' composition was analyzed and the temperature inside the bed was measured with high frequency (1 s⁻¹). A video camera was used to record the dynamics of the process.

Table 2 shows data from the incineration process: the emission levels of exhaust gases such as NOₓ, CO, CO₂, SO₂ and temperature readings. The emission levels were normalized according to the Ministry of Environment decree (22.04.2011) to a reference level of oxygen's concentration at 6%. Thermal transformation was performed under a high temperature within the range 820 – 840 °C. Incineration of every sample meets the said emission norms of NOₓ, CO₂ and SO₂. The highest concentration of nitrogen oxides was
recorded during combustion of the sample containing the integrated circuit (84.2 mg/m$^3$). However, other samples yielded similar levels of concentration. The larger concentration of nitrogen oxides may have resulted from the higher mass of the sample. Furthermore, during the incineration the concentration level of carbon monoxide was 544 – 777 mg/m$^3$. This is not a high level considering that no additional burning chamber was used and such chambers significantly lower the CO concentration in exhaust fumes.

Table 2. Results of emission levels and temperature measuring during combustion of PCB elements in a fluidized bed.

<table>
<thead>
<tr>
<th></th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
<th>Sample D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2$ [%]</td>
<td>6.2</td>
<td>5.7</td>
<td>6</td>
<td>5.7</td>
</tr>
<tr>
<td>$SO_2$ [ppm]</td>
<td>4.1</td>
<td>4</td>
<td>4.1</td>
<td>3.7</td>
</tr>
<tr>
<td>CO [ppm]</td>
<td>265</td>
<td>250</td>
<td>188</td>
<td>204</td>
</tr>
<tr>
<td>$CO_2$ [ppm]</td>
<td>9.2</td>
<td>9.6</td>
<td>9.4</td>
<td>9.6</td>
</tr>
<tr>
<td>$NO_x$ [ppm]</td>
<td>25.2</td>
<td>29.7</td>
<td>22.9</td>
<td>20</td>
</tr>
<tr>
<td>$T_1$ [°C]</td>
<td>817</td>
<td>825</td>
<td>824</td>
<td>823</td>
</tr>
<tr>
<td>$T_2$ [°C]</td>
<td>833</td>
<td>840</td>
<td>842</td>
<td>834</td>
</tr>
</tbody>
</table>

Normalized to 6% of $O_2$ in the exhaust fumes

<table>
<thead>
<tr>
<th></th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
<th>Sample D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SO_2$ [mg/m$^3$]</td>
<td>41.3</td>
<td>37.5</td>
<td>14.3</td>
<td>36.1</td>
</tr>
<tr>
<td>CO [mg/m$^3$]</td>
<td>777</td>
<td>711</td>
<td>544</td>
<td>579</td>
</tr>
<tr>
<td>$NO_x$ [mg/m$^3$]</td>
<td>74</td>
<td>84.2</td>
<td>66.3</td>
<td>56.6</td>
</tr>
</tbody>
</table>

$T_1$ – temperature inside the bed at 20 mm; $T_2$ – temperature inside the bed at 50 mm

Figure 3 shows the dynamics of the incineration process for the studied PCB fragments. The image was recorded with a digital video camera placed perpendicularly in relation to the reactor's axis. This allowed to gather additional information on the combustion process of the samples. The most relevant frames were extracted from the film. Figure 3 shows 4 pictures for each sample that illustrate the process. The highest dynamics of the incineration process can be seen for the sample containing large amount of plastic (sample D) and the one containing the integrated circuit (sample D). The lowest dynamics can be seen for the laminate containing no electronic parts (sample A).

During the combustion of each sample large exploding bubbles were observed inside the fluidized bed, which ignited the flammable gas mixture. The combustion occurred in a continuous manner and the portions of gas and the resulting explosions ensured the high temperature of the bed and supported a very good transfer of both heat and mass. Intensification of the process for the samples of the integrated circuit and the plastic part (samples B and D) was so large that at certain points the samples were thrown even above the bed's surface (picture B2 and D4).

During combustion of all the pieces of the PCB we can see a rare dispersed phase above the bed. The largest area of this phase can be seen during combustion of the plastic part. When the piece was put into the reactor we can see not only an exploding bubble, a flame but also the grains rising towards the dispersed state (picture D1).

Incineration of the piece that had condensers welded onto it (sample C) the combustion was rather dynamic but very short (this was the smallest PCB fragment).
Figure 3. Dynamics of the incineration process of PCB fragments.
Rysunek 3. Dynamika procesu spalania fragmentów obwodu drukowanego.
3. Conclusions

- Incineration of PCB fragments inside a fluidized bed reactor allows to burn out the polymer part and leaves us with the non-combustible part.
- Concentration levels of exhaust gases meet the environmental norms set by the Ministry of Ecology 22.04.2011.
- Thermal transformation of electronic fragments was periodical and under good conditions of heat and mass exchange.
- Dynamics of the incineration process is influenced by the mass of the fragments and their composition (amount of electronic parts).
- The highest intensity of incineration occurred during combustion of the fragment containing a significant amount of plastic parts, the one containing an integrated circuit that also had the largest mass. The least intense incineration occurred with the sample that had not electronic components.

References

[14] Rozporządzenie Ministra Środowiska z dnia 22.04.2011r. w sprawie standardów emisyjnych z instalacji, Dziennik Ustaw z 2011 r. Nr 95 poz. 558.

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Dynamika procesu spalania elementów obwodów drukowanych w reaktorze fluidyzacyjnym

Słowa kluczowe

ZSEE – obwód drukowany – reaktor fluidyzacyjny

Streszczenie

W artykule przedstawiono metodę termicznego przekształcania elementów obwodów drukowanych pochodzących z płyty głównej komputera. Proces spalania przeprowadzono w reaktorze laboratoryjnym ze złożem fluidalnym. Podczas procesu prowadzono stały monitoring zawartości w spalinach takich gazów jak: NOₓ, CO, CO₂, SO₂. Ponadto przedstawiono dynamikę poszczególnych elementów obwodu drukowanego.