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Mathematical analysis of the gas–solid fluidized bed separation of metals and nonmetals from waste PCB powders

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ABSTRACT

Modern society is generating increasing quantities of waste printed circuit boards (PCBs). Together with the complicated components of high values, the treatment of waste PCBs has been a heavily researched and difficult topic in the disposal of waste electrical and electronic equipment (WEEE). The application of an air separation technology to produce comminuted PCB particles can achieve efficient separation of metal and nonmetallic fractions for further treatment and purification. With the advantages of a simple operation, environmental-soundness, and avoidance of secondary pollution, this technology is of great significance in the recycling of waste PCBs. In this paper, the air separation principles of waste PCB particles in a fluidized bed were mathematically analyzed. The shape factor of metal and non-metallic particles and the uneven airflow velocity distribution in the radial dimension were considered, and the formula for metal grade and yield were deduced. Experiments were designed and performed to obtain metal grade and yield data, which were compared with the calculation results. The calculated grade is in good agreement with the experimental results. The presented mathematical analysis can act as a guide for the engineering design and operating configuration of air separation for waste PCB particles in determining the terminal velocity and for selecting the particle size, feed volume, and discharging height.

1. Introduction

PCBs are widely used in various types of home appliances and consumer electronic products. With the rapid development of technology and the increase of human living standards, home appliances and consumer electronic products have exhibited a notable growth in the last several decades. Subsequently, this phenomenon has resulted in a huge amount of electronic waste containing PCBs. The manufacturing process of electronic products has also produced a large quantity of scrap PCBs. For improved sustainability, to recover high value materials, and in response to regulatory requirements, such as extended producer responsibility for WEEE, research of WEEE treatment and recovery has attracted considerable attention recently. The safe and effective treatment of waste PCBs, characterized by large quantities, complicated components, high potential value, and high hazards, has increasingly become a heavily researched topic and key technical problem in WEEE treatment.

PCBs are normally composed of ~60% nonmetals and ~40% metals, containing nearly all elements of the periodic table and thus are highly complicated. The nonmetallic components are primarily composed of, for instance, epoxy resin, brominated flame retardants, and glass fiber [1]. The metal components are comprised of heavy metals, such as Cu, Sn, and Pb, and precious metals, such as Au and Ag. Normally, Cu consists of approximately 80% of all metals [2]. The content of precious metals in waste PCBs is 10 times greater than that of rich-content mineral ores [3]. Therefore, waste PCBs deserve the name of “golden mine” [4]. Obviously, PCBs have a very high recovery value. At the same time, because waste PCBs contain highly toxic heavy metals and polymeric bromine flame retardants, waste PCBs can cause huge negative impacts on soil, air, and water and thus can damage human health [5,6] if treated by methods, such as incineration and acid washing, which are still used in some countries. Polymeric bromine flame retardants can cause endocrine disorders, increase the incidence of lymph and digestive system cancers, and produce the potent carcinogens dioxin and furan [7,8] when incinerated.

The effective separation of these metallic and nonmetallic materials based on the differences in their properties is the key for developing a recycling methodology for waste PCBs. Considering separation principles, recycling technologies can be categorized into mechanical/physical methods, hydrometallurgical methods, heating methods, biological methods, and supercritical fluid methods. These technologies are very different in terms of the economic feasibility, operational complexity, recovery efficiency, and environmental impact.

Before the 1990s, the main recycling methods for waste electronic equipment (including waste PCBs) in Europe and America were heating, the hydrometallurgical process, and electro-deposition [9], primarily aimed at recycling precious metals, e.g., gold, silver, copper, and lead. These methods may cause environmental pollution and omit the recycling of other valuable materials. An organic solvent, dimethyl sulfoxide (DMSO) [10], was used to extract brominated epoxy resin

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from waste PCBs and was regenerated by vaporization under decompression. However, it is still very difficult to further separate the residue from the epoxy resin obtained. The high energy consumption, operational complexity, and potential organic emissions have precluded the expansion of this process to the plant scale. Biological methods and supercritical fluid methods, with their limitations and immaturity, are also difficult to implement widely.

Due to the combination of environmental-soundness, low energy consumption, and separation efficiency, mechanical/physical methods have become the mainstream techniques used to comprehensively recycle and reuse the components in waste PCBs [11]. These mechanical/physical methods can be broadly divided into two major steps: Comminution and then separation. In the first major step, i.e., comminution, the individual components of the PCBs are liberated from each other. Experiment results have shown that total metal liberation, which is the prerequisite for effective separation, can be more or less achieved for comminuted particles smaller than 1 mm [12]. The liberated components are separated in the second major step, where electric separation, magnetic separation, and gravity separation could be employed due to differences in the shapes, magnetic properties, electronic properties, and densities of the PCB compenents. For example, in corona electrostatic separation, i.e., one of the electrical separation methods, the granular mixture to be separated is fed onto the surface of a rotating roll and passed through an electric field. After intensive ion bombardment, the insulating particles are charged and pinned to the surface of the roll electrode, while the conducting particles lose their charge to the grounded rotor, thus achieving separation [13]. Gravity separation methods, based on the difference in the densities of metallic and nonmetallic fractions, include jigging [14,15] and air separation [16] with the use of water and air as fluids. Both jigging and air separation adopt the same separation principle. In a moving fluid, particles with smaller sizes or lower densities will flow out with the media, while ones with larger sizes or higher densities will stay, thus achieving the separation of heavy and light fractions. Gravity separation, with the advantages of simple equipment, low operating cost, and continuous operation etc., has been widely used worldwide. For example, jigging has been widely utilized in the mineral processing industry to concentrate relatively coarse materials. Although both water-solid fluidized bed (e.g., jigging) and gas–solid fluidized bed separations have been widely used in the recycling of waste PCBs [17], separation via an air-solid fluidized bed can avoid the generation of large amounts of waste water and subsequent secondary contamination and save the energy required to dry the metal particles [18]. It is thus the more promising technique and worth studying for further design and operation optimization. This paper is focused on this topic.

After separation by the gas–solid fluidized bed technology, recycled metallic and nonmetallic fractions can be further purified and recycled. Metals, such as Cu, Al, Fe, Sn, Sb, and Pb, are sent to recovery operations, and these processes are already notably mature. The nonmetallic fraction can be pyrolyzed to obtain liquid and gas organic materials [19–22], or in the form of powder, they can be used as reinforcing materials, as insulation materials or for paving material manufacturing, as fillers for plastic manufacturing [23–25], or even be activated to become absorbents [26].

Although some research projects on the separation by gas–solid fluidized beds have been reported, very few reports have focused on the mathematical analysis of its process to provide an engineering guide of the air separation system. This study includes the theoretical analysis, mathematical calculation, and experiments designed to verify the calculated results, which aim to provide an engineering guide in the design and operation configuration of particle sizes, feeding volumes and discharging points. First, the separation principle of waste PCB particles in a fluidized bed is mathematically analyzed, and the formula of metal grade and yield are deduced under ideal operating conditions. Next, the influences of shape factor and airflow velocity radial distribution on air separation through the terminal velocity are considered and used to modify the formula of metal grade and yield. Finally, experiments are designed and conducted to obtain the metal grades and yields under various operating conditions, which are compared with the calculated results. The discrepancies between the experimental results and the calculated results are analyzed, and possible explanations are given.

2. Experimental section

2.1. Experimental materials

In the study, scrap PCBs of relatively uniform compositions generated during manufacturing were used. The nonmetallic components consisted primarily of a resin and a small amount of glass fiber, while the metallic components were predominately copper. A Taylor sieve was employed to screen the comminuted powders.

The properties of comminuted powders in this study are shown in Table 1. In general, the initial metal grade decreased with the decrease of particle size, meaning that smaller sized particles contained more nonmetal content. In this study, the average particle size $d_{ave} = (d_{max} + d_{min})/2$ was used to represent the particle size.

2.2. Separation of metals and non-metals by the gas–solid fluidized bed technology

Fig. 1 shows a schematic diagram of the fluidized bed separator.

The operation of the fluidized bed is as follows. First, a measured amount of PCB powder was charged into the fluidized bed via feed inlet 6. Blower 1 is turned on to convey air into the fluidized bed. The air flow rate was adjusted with valve 2 and measured by flow meter 3. The powder was fluidized and entered cyclone 7 when the air flow rate was increased to a certain level. PCB particles were collected in the cyclone. Very fine powders were captured by bag filter 8, and filtered air was emitted to the atmosphere.

2.3. Analysis and measurement

The pre and post separation samples were pretreated in a microwave digestion instrument, and then a flame atomic absorption spectrometer was employed to determine the metal content. Below are the main parameters of the spectrometer:

Equipment model: AAnalyst 400
Equipment manufacturer: American PerkinElmer Inc.
Limit of detection: ppm–ppb grade

3. Mathematical analysis of gas–solid fluidized bed separation

3.1. Particle movement analysis during gas–solid fluidized bed separation

Fig. 2 shows the forces acting upon an individual particle settling in the fluid. There are three main forces, i.e., a gravity force F_g, a buoyancy force F_b, and a drag force F_d. The sum of the buoyancy force and the drag force can be considered as the pure gravity force acting on the particle [27].

For a particle at rest, there will be no drag force, which causes the particle to accelerate due to the gravity force. As the particle increases in velocity, the drag force and the pure gravity force will eventually become approximately equal, causing no further change in the particle's velocity. Eq. (1) shows the resultant force:

$$F_t = F_g - F_b - F_d \tag{1}$$

At this point, the particle is in a uniform motion state or suspension state. The forces are:

$$F_g - F_b = F_d \tag{2}$$