Effect of Orifice Introduction on Floating Characteristics of Cuboid Particles Simulating Tantalum Capacitors in Pneumatic Separation Column

Naohito Hayashi* and Tatsuya Oki

Research Institute for Environmental Management Technology, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8569, Japan

To recycle important rare metals (such as tantalum) from the printed circuit boards of waste electronic equipment, devices must first be delaminated from the boards. The devices are then separated into individual device types. For the practical use of the separation process, the authors previously developed a double-tube pneumatic separator. One of the features of this equipment is the introduction of orifices in a pneumatic separation column; an air-solid multiphase flow simulation was conducted to clarify its effect. The effects of the orifices on the floating characteristics and floating rates of cuboid particles and spherical particles with the same solid volume and mass as the cuboid particles were investigated for cases in which the number of orifices and the volumetric airflow rate in the separation column varied. The results showed that the floating characteristics of cuboid particles were much different from those of spherical particles. It was estimated that the volumetric airflow rate could be decreased by 14% with the cuboid particles and the same particle recovery could still be achieved. When the volumetric airflow rate was identical, the treatment throughput for the cuboid particles was expected to increase by 20–30%. These results were caused by the difference in the cross-sectional areas of the particles, which indicates that taking the particle shape into account is extremely important for the numerical simulation of pneumatic separation. To thoroughly recover the cuboid particles, it is ideal to use a volumetric airflow rate greater than 0.129 m³·s⁻¹ or less than 0.0615 m³·s⁻¹, regardless of the orifice introduction. The number of orifices had no effect on either the separation efficiency or floating rate in the range of 0.118–0.129 m³·s⁻¹. On the other hand, it was shown that the floating rate clearly changed depending on whether the orifices were introduced or not for the 0.103 m³·s⁻¹ case. [doi:10.2320/matertrans.M2014818]

(Received January 8, 2014; Accepted March 7, 2014; Published April 18, 2014)

Keywords: pneumatic separation, orifice, air-solid multiphase flow, numerical simulation, discrete element method, printed circuit boards, tantalum capacitor, rare metals

1. Introduction

The printed circuit boards (PCBs) used in electronic equipment include copper films, gold coatings, and electronic devices containing specific precious and rare metals. For example, tantalum capacitors contain Ta, Mn, and Ag; ceramic capacitors contain Ba, Ni, Ag, and Pd; and thermistors contain Ni, Pt, and Pd. Recycling systems are highly desired to ensure a stable supply of these metals. However, because the Cu and precious metals constitute the major economic value of waste PCBs, recycling is largely restricted to recovery using a copper smelting process. In this process, many rare metals such as Ta (selected by the Japanese government in 2012 as one of five rare metals to be recycled) are easily oxidized and distributed into slag. Retrieving rare metals from slag, however, is not economically viable.

Therefore, the recovery of the main rare metals from waste PCBs must proceed in two steps: the delamination of electronic devices from waste PCBs and the separation of the electronic devices containing specific rare metals. The delamination of electronic devices is typically performed using a conventional impact crusher. The efficient separation of specific device types from a mixture of electronic devices, on the other hand, has proven to be very difficult. If a high-accuracy separation method could be devised, the target metals could be recovered from specific types of the separated electronic devices using conventional hydrometallurgical processes.

One of the authors, Oki(4,5) showed that tantalum capacitors could be recovered efficiently from a mixture of electronic devices delaminated from waste PCBs at both a recovery ratio and grade of approximately 90% by using the following three physical separation processes: two-stage screening, preliminary separation on the basis of differences in the shape and magnetic property, and gravity concentration using a double tubes pneumatic separator. He also succeeded in commercializing a tantalum capacitor recovery system that combined these processes with electronic device delamination using an impact crusher. Here, in the preliminary separation, the simultaneous recovery of quartz resonators with high iron content and aluminum electrolytic capacitors with a cylindrical shape, which tended to roll, was achieved by using a magnetic separator on an inclined belt.

The double tubes pneumatic separator consisted of two connected separation columns with different cross-sectional areas standing vertically. It was possible to separate particles with three different densities (light, middle, and heavy) from their mixture using this equipment. Tantalum capacitors could be recovered as middle-density particles at a high probability through the proper control of the volumetric airflow rate in the columns. There were five original features in this equipment: (1) the airflow velocity profile at the cross section of the column was mostly flat, (2) the cross-sectional area of the second column could be varied easily to produce a small difference between the airflow velocities in the two columns, (3) a special joint design was used to connect the columns smoothly, (4) an automatic control program based on the previous experimental data was used, and (5) the separation rate was increased by the introduction of orifices in the columns. The effect of these orifices, which reduced the inner diameter of the column over a short distance, was similar to that reported by Ito et al. In their experiments, the separation rate of Cu and Al plate samples increased when a

*Corresponding author, E-mail: n hayashi@ aist.go.jp
pneumatic separation technique was applied; in addition, the separation efficiency was retained with reduced airflow and was less affected by variations in the volumetric airflow rate. Oki et al.\(^9\) experimentally demonstrated, however, that pneumatic separation produces little increase in either the separation efficiency or rate in the case of spherical particles (unlike the rectangular or plate particles mentioned previously). The authors\(^{10}\) proved through the numerical simulation of spherical particle trajectories in the column that there was an optimal distance between the orifices to maximize the separation rate, with no increase in the separation efficiency.

Therefore, taking into account pneumatic separation using the double tubes pneumatic separator, we attempted to clarify the effect of orifice introduction on the floating characteristics of cuboid particles used to simulate tantalum capacitors in a separation column. For this purpose, cuboid particles consisting of small spherical particles were made, and a numerical simulation of air–solid multiphase flow combining the finite volume method (FVM) with the discrete element method (DEM) was conducted. We quantitatively investigated the effects of orifices on the floating recovery ratio of the particles and their average residence time in the column.

2. Methods

2.1 Simulation model

The detailed explanation of the simulation model constructed is omitted here because it corresponded to that in the previous study.\(^{10}\) Just as in the previous study, we adopted a versatile software program, R-FLOW, developed by R-flow Corporation Ltd., to simulate the air–solid multiphase flow. Figure 1 shows an outline of the experimental apparatus used; the calculation region is shown as a solid line. The diameter and height were 84 and 1625 mm, respectively. The bottom and top of the column were designated as the inlet and outlet of the airflow, respectively.

A specified number of orifices were inserted at equidistant intervals \(L\) (mm) along the column. The distance between the inlet and the first orifice was set at 275 mm (height from the mesh center: 500 mm). The inner diameter, height, and angle of each orifice were 74 mm, 50 mm, and 45°, respectively; these values were the same as the dimensions and orientation of the experimentally used orifice.\(^{10}\)

2.2 Airflow analysis

The calculation region was divided into 320,000 control volumes for the airflow analysis: 20 in the radius direction, 64 in the cylindrical direction, and 500 in the axial direction. The average control volume was 29 mm\(^3\). The time-averaged Reynolds equations were solved numerically for each control volume. The standard \(k\)-\(\varepsilon\) model was used as a turbulence model.

Prior to the air–solid multiphase flow simulation, a steady flow simulation was conducted in air at ambient temperature (density: 1.2 kg m\(^{-3}\), viscosity: \(1.8 \times 10^{-5}\) m\(^2\) s\(^{-1}\)) in a volumetric airflow rate range of 0.0621–0.129 m\(^3\) s\(^{-1}\) (average velocity at inlet: 11.2–23.2 m s\(^{-1}\)). In the above simulation, the airflow velocity profile at the inlet was estimated and set using the method explained in the previous paper,\(^{10}\) considering the existence of the mesh for heavy particle recovery. This setting caused the airflow velocity profile at the inlet to be deflected along the \(x\) direction. Figure 2 shows, for example, the airflow velocity profile at the inlet in the case of a volumetric rate of 0.0665 m\(^3\) s\(^{-1}\).

The effect of the equal distances between orifices, \(L\), was investigated in the steady flow simulation by varying the
number of orifices from 0 to 5 and observing the resulting velocity profiles. Here, \( L \) was 1625 mm in the case without orifices and 1300, 625, 400, 287.5, and 220 mm in the cases with 1, 2, 3, 4, and 5 orifices, respectively.

### 2.3 Air–solid multiphase flow analysis

To analyze the behavior of the model particles in the column, the DEM\(^{11} \) was applied. A cuboid particle composed of a total of 140 spherical particles with a diameter of 1 mm (density: 3490 kg·m\(^{-3} \)), in an array with seven, five, and four particles rigidly connected in the \( x, y, \) and \( z \) axial directions, respectively, was constructed as a model particle to simulate a large-size tantalum capacitor of the molded-in resin type. Figure 3 shows a cuboid particle made. The physical properties used in the simulation model on the basis of the DEM were the same as those in the previous paper\(^{10} \) and are summarized in Table 1. The diameter of a spherical particle with the same volume as the solid volume of the cuboid particle (identical to the total volume of 140 spherical particles with a diameter of 1 mm, 73.3 mm\(^3 \)) was 5.19 mm, and its terminal velocity was estimated to be 23.2 m·s\(^{-1} \).

The FVM was coupled to the DEM with respect to the drag force of the airflow on the particles to analyze the air–solid multiphase flow. Because the considered volume ratio of particles in the column was rather low (less than 0.1%), the airflow was not changed by the particle flow (one-way coupling method). The apparent volume of the cuboid particle including void was 140 mm\(^3 \) and approximately five times larger than the control volume for airflow analysis (average 29 mm\(^3 \)); therefore, the cuboid particle was divided averagely into five control volumes, and the velocity vector of each control volume was used in the simulation. Because the simulation was conducted on the basis of the one-way coupling method, the calculation of the velocity profile in the column did not take into account the actual phenomenon that air flowed along with the cuboid particles. Because the size of the cuboid particle was comparatively large, the drag forces, \( F_D \) (N), in the axial directions of \( x, y, \) and \( z \), were calculated using the following equation:

\[
F_D = \frac{1}{2} A_p \rho_a C_D |v_g - v_p|(v_g - v_p)
\]

Here, \( A_p \) (m\(^2 \)), \( \rho_a \) (kg·m\(^{-3} \)), \( C_D \) (1), \( v_g \) (m·s\(^{-1} \)), and \( v_p \) (m·s\(^{-1} \)) are the apparent cross-sectional area of the particle, air density, drag coefficient, air velocity, and particle velocity, respectively. The obtained drag force, \( F_D \), was divided into equal parts for the individual spherical particles that were used to compose the cuboid particle.

To inject the cuboid particles, five particles were aligned side by side parallel to the \( y \) axis at a feeding point 50 mm above the inlet and fed at \(-1\) m·s\(^{-1} \) in the \( x \)-axial direction. The initial posture of the particles was set the same as shown in Fig. 3 (also the same as the initial posture in Fig. 4(b)). In this experiment, to prevent giving either an upward or downward (in the \( z \)-axial direction) velocity, the tantalum capacitors were fed through a guide rail with a smooth slope from the column side to the center. The initial particle velocity was set at \(-1\) m·s\(^{-1} \) in the \( x \)-axial direction, which was the same as the high-speed camera measurements of the tantalum capacitors fed into the column. The cuboid particles were released every 0.18 s. Thus, the feed rate was 25 kg·h\(^{-1} \), which was the same as that in the experiment. In addition, cases where spherical particles with a diameter of 5.19 mm were fed at the same position and feed rate were calculated.

A velocity profile was obtained using an airflow analysis for each number of orifices. The particle behavior attained a near-steady state 5 s after the start of feeding; therefore, the calculation was continued for 10 s to achieve an unambiguous steady state.

### 3. Results and Discussion

#### 3.1 Airflow analysis

A steady simulation was conducted while changing the number of orifices from 0 to 5. The volumetric airflow rate was varied from 0.0621 to 0.129 m\(^3\)·s\(^{-1} \). The results showed that the characteristics of the velocity profile were identical to the case with 0.0665 m\(^3\)·s\(^{-1} \) (velocity at inlet: 12.0 m·s\(^{-1} \)), as reported in the previous paper.\(^{10} \) The primary characteristics are listed below.

- In the absence of orifices, the velocity profile remained eccentric at distances exceeding 1 m. When multiple orifices were introduced, however, the velocity eccentricity was corrected beyond the second orifice.
- The eccentricity ratio of the velocity profile was decreased with an increase in the number of orifices.
- When the distance between orifices was 400–625 mm, it was expected that high-speed and high-efficiency separation had been achieved, and that step-by-step separation had been attained in a single separation column.
3.2 Air–solid multiphase flow analysis
3.2.1 Trajectory of cuboid particle after being fed

Figures 4(a) and 4(b) shows the typical trajectories of a tantalum capacitor in the experiment and a cuboid particle calculated in the simulation after being fed, respectively. The volumetric airflow rate was 0.129 m³/s⁻¹. Figure 4(a) shows that after being fed almost horizontally, the tantalum capacitor moved to the left and slightly upward, where it collided with the left inner wall of the column. It then moved vertically and rotated three-dimensionally. It can be said that the same trajectory could be replicated more often in the simulation compared with the trajectory in Fig. 4(b). Because the particle trajectories were expected to change most dramatically just after being fed, we decided that adequate calculation results were obtained by the simulation method used.

In the experiment, tantalum capacitors definitely moved upward and rotated three-dimensionally after collision with the left inner wall, because it was impossible to feed perfectly at the center of the column. On the other hand, when the cuboid particles were fed at the center of the column (\( y = 0 \)) in the simulation, they collided with the left inner wall and moved upward while rotating two-dimensionally along the \( y \) axis. This was because the \( y \) component of the airflow velocity in the column was mostly zero. Therefore, the \( y \) coordinate of the initial position of the cuboid particle was staggered 5 mm from the column center.

3.2.2 Effect on floating characteristics

Figure 5 shows the calculation results for the ratio of cuboid particles blown upward by the airflow and recovered at the outlet in the cases where the number of orifices varied from 0 to 5. A 0% recovery ratio indicates that all the particles had been dropped and recovered at the inlet. The horizontal axis shows the number of orifices. In addition, Fig. 5 shows the calculation result of the spherical particles (diameter: 5.19 mm) without orifices (showing as “sphere & 0”) and the experimental result using tantalum capacitors with 2 orifices (showing as “orifice 2 (exp)”).

From Fig. 5, compared with the experimental and calculated results for the case of two orifices, it turned out that the floating recovery ratio obtained in the experiment was slightly larger than that obtained in the simulation in the volumetric airflow rate range of 0.085–0.1 m³/s⁻¹, but a qualitatively precise estimation could be conducted. Taking the particle shape into account in the calculation of the drag force seems to be essential for the numerical simulation of a pneumatic separation process.

It is obvious that the floating characteristics of the spherical particles were different from those of the cuboid particles, and a larger volumetric airflow rate was necessary to blow the spherical particles upward. This tendency was identical to the experimental result of Ito et al. using metal plate samples. Because the terminal velocity of the spherical particles was 23.2 m/s⁻¹, which was identical to 0.129 m³/s⁻¹, almost all the spherical particles floated; the volumetric airflow rate needed to attain a 50% floating recovery ratio was approximately 0.11 m³/s⁻¹. On the other hand, for the cuboid particles, the volumetric airflow rate for a 50% recovery was approximately 0.095 m³/s⁻¹; this indicates that a 14% lower volumetric airflow rate was necessary compared with the case of spherical particles. Therefore, the terminal velocity for the equivalent volumetric spherical particle cannot be used as a reference to select a volumetric airflow rate for the pneumatic separation of cuboid particles. This is thought to be because the apparent cross-sectional area of the cuboid particles, which moved upward while rotating three-dimensionally in the \( z \)-axis direction, was larger than that of the spherical particles in time averaging. The apparent cross-sectional area for the \( z \)-axis direction at the initial position of the cuboid particles (35 mm²) was approximately 40% larger than that of the spherical particles (21.1 mm²); however, the decrease in the volumetric airflow rate remained 14% because of the three-dimensional rotation of the cuboid particles.

Considering the calculation results using the cuboid particles, it was found that, when the volumetric airflow rate was more than 0.129 m³/s⁻¹ or less than 0.0615 m³/s⁻¹, the floating recovery ratio was usually 100 or 0%, respectively. Under these conditions, the number of orifices had no effect on the recovery ratio. On the other hand, in the case of volumetric airflow rates ranging from 0.0615 to 0.129 m³/s⁻¹, the floating recovery ratio obtained without orifices was lower than that obtained when orifices were introduced. Especially in the 0.09 m³/s⁻¹ case, a difference in the floating recovery ratio was seen, depending on the number of orifices, and the recovery ratio tended to increase with an increase in
the number of orifices. This is because the ratio of the comparatively high-velocity region in the column increased with an increase in the number of orifices. This indicates that the range of volumetric airflow rates in which the number of orifices affected the floating characteristics was not very wide.

Therefore, it is ideal to use a volumetric airflow rate of approximately 0.129 or 0.0615 m³/s to guarantee the recovery of tantalum capacitors (at either the outlet or inlet) during their actual pneumatic separation. However, it is thought that there is some possibility that the other types of electronic devices will show the same trajectories as tantalum capacitors, depending on the device type or their destruction condition; this will make the high-grade recovery of tantalum capacitors difficult. In that case, a volumetric airflow rate in the range of 0.0165 to 0.129 m³/s should be used. If a rate of approximately 0.09 m³/s is selected, it is necessary to decide on the number of orifices while considering their effect on the separation efficiency.

This time, the velocity profile was calculated on the basis of the one-way coupling method, in which the velocity profile was not affected by the particle trajectory. Therefore, it can be said that an actual local change in a velocity profile caused by an airflow that carries along the tantalum capacitors has little effect on their floating and sinking trajectories.

3.2.3 Effect on floating rate

Figure 6 shows the calculation and the experimental results for the average residence time of cuboid particles in the column. The residence time denotes the time between feeding and discharge from the outlet or inlet. In this figure, the range of the volumetric airflow rates was restricted to 0.103–0.129 m³/s, considering the high floating recovery ratio.

The calculated residence times of the cuboid particles agreed rather well with the experimental ones using tantalum capacitors in the case of 2 orifices introduction. Therefore, it can be said more precise simulation could be conducted by using the cuboid particles also from the point of view of residence time estimation.

The residence time became shorter with a higher volumetric airflow rate and ranged between 0.68 and 2.1 s. The residence time of cuboid particles was shorter than that of spherical particles: 20–30% shorter at the same volumetric airflow rate. This indicated that the floating rate of the cuboid particles was higher, and that a 20–30% larger treatment throughput could be attained at the same volumetric airflow rate. As to the difference in the number of orifices, there was little effect in the range from 0.118 to 0.129 m³/s. Therefore, it turned out that, when using a volumetric airflow rate in this range, the orifice introduction and number of orifices had little effect on either the separation efficiency or floating rate.

On the other hand, a significant difference in the average residence time was seen depending on the orifice introduction in the case of a volumetric airflow rate of 0.103 m³/s. This was because the effect of the orifice introduction, which led to an increase in the high-velocity airflow region in the column, became relatively greater at such a volumetric airflow rate. The simulation conducted this time did not take into account the trajectories of other types of electronic devices, which would actually exist together with tantalum capacitors; therefore, it is impossible to optimize the process conditions such as the volumetric airflow rate and number of orifices based solely on the abovementioned results. However, from the point of view of the amount of throughput for tantalum capacitors, at least one orifice should be introduced when the volumetric airflow rate is approximately 0.103 m³/s.

4. Conclusions

To clarify the effect of orifice introduction in a pneumatic separation column, which is one of the features of the double tube pneumatic separator that has been used for the successful recovery of tantalum capacitors from a mixture of waste electronic devices, an air–solid multiphase flow simulation was conducted. Cuboid particles were used to simulate tantalum capacitors, and the effects of their trajectories on their floating characteristics and recovery rate were analyzed, when the number of orifices and volumetric airflow rate were varied. The results are summarized as follows:

(1) An air–solid multiphase flow simulation was conducted assuming that the volumetric ratio of the control volume for the airflow analysis and the cuboid particle was set at 1:5, and that the one-way coupling method was used, in which the velocity profile was not affected by the particle trajectories. The results showed that the calculated particle trajectories, which were thought to change dramatically just after being fed, were qualitatively identical to the experimentally observed trajectories of tantalum capacitors. In addition, the calculated results for the floating characteristics of cuboid particles were similar to the experimental results in the case of introducing two orifices.

(2) The floating characteristics of spherical particles with the same volume and mass as the cuboid particles were considerably different from those of the cuboid particles. To recover each to the same extent, it turned out that the volumetric airflow rate for the cuboid particles had to be decreased by 14%. With the same volumetric airflow rate, a 20–30% increase in the treatment throughput is expected for cuboid particles.
This is thought to be because the apparent cross-sectional area in the z-axis direction of cuboid particles, which moved upward while rotating three-dimensionally, was larger than that of spherical particles in time averaging.

(3) To guarantee the recovery of the cuboid particles, the volumetric airflow rate should be more than 0.129 m³·s⁻¹ or less than 0.0615 m³·s⁻¹, regardless of the orifice introduction. In the range of volumetric airflow rates from 0.0615 to 0.129 m³·s⁻¹, especially in the 0.09 m³·s⁻¹ case, it was revealed that the floating recovery ratio increased with the number of orifices. This was because the ratio of the comparatively high-velocity region in the column increased with an increase in the number of orifices. Therefore, it can be said that the range of volumetric airflow rates in which the number of orifices affected the floating characteristics was not very wide.

(4) It turned out that, when using a volumetric airflow rate in the range of 0.118–0.129 m³·s⁻¹, the orifice introduction and number of orifices had little effect on either the separation efficiency or the floating rate. On the other hand, a significant difference in the average residence time was seen depending on the orifice introduction in the case of a volumetric airflow rate of 0.103 m³·s⁻¹.

REFERENCES