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Journal of Hazardous Materials 153 (2008) 1308–1313
Journal of Hazardous Materials
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# Theoretic model and computer simulation of separating mixture metal particles from waste printed circuit board by electrostatic separator

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Received 1 August 2007; received in revised form 5 September 2007; accepted 21 September 2007
Available online 29 September 2007

**Abstract**

Traditionally, the mixture metals from waste printed circuit board (PCB) were sent to the smelt factory to refine pure copper. Some valuable metals (aluminum, zinc and tin) with low content in PCB were lost during smelt. A new method which used roll-type electrostatic separator (RES) to recovery low content metals in waste PCB was presented in this study. The theoretic model which was established from computing electric field and the analysis of forces on the particles was used to write a program by MATLAB language. The program was design to simulate the process of separating mixture metal particles. Electrical, material and mechanical factors were analyzed to optimize the operating parameters of separator. The experiment results of separating copper and aluminum particles by RES had a good agreement with computer simulation results. The model could be used to simulate separating other metal (tin, zinc, etc.) particles during the process of recycling waste PCBs by RES.


*Keywords:* Computer simulating; PCB scraps; Mixture metal particles; MATLAB

## 1. Introduction

The waste printed circuit board (PCB) is increasing worldwide. Recycling of PCB is an important subject not only from the treatment of waste but also from the recovery of valuable materials [1,2]. The corona electrostatic separation was proved to be an efficient and environmental way for recovering metals from PCB scraps [3]. The separated metal particles after corona electrostatic separation always mixed with different metals (such as copper, aluminum, tin, zinc, etc.). Traditionally, the mixture metals was sent to smelt factory and refined to pure Copper. Some valuable metals (aluminum, zinc and tin) with low content in PCB were lost during smelt and waste these resources.

Simple and reliable roll-type electrostatic separation (RES) has been investigated extensively in the minerals processing industry for recycling metals. But there is not relevant research about using RES to separate different metals. A study [4] only established a theoretic model for computing the trajectory of solo conducting particle from waste PCB in RES. However, the metal particles from waste PCBs were mixture (such as copper, aluminum, tin, zinc, etc.). How to separating and recycling these resources was an important object. The aim of this paper is to show that the RES can be successfully employed for separating different metal particles. On the basis of theoretic model [4], a program by MATLAB language was wrote. The program was designed to simulate the process of separating mixture metal particles. The operating parameters of RES: electrical, material and mechanical factors were analyzed to optimize the operating parameters of separator.

## 2. Principle of proposed method

The separator consists of a rotating roll, connected to the ground, and a high-voltage electrode (Fig. 1). The materials were fed on the rotating roll by an electric shaker. Apart from the electric force involved in the electrostatic separation system, the gravitational force, centrifugal force and other mechanical forces are also present. At first, the metal particles were moved with rotating roll. When the co-acting forces on them satisfied special condition, the particles detached from the rotating roll. Therefore, different metal particles have different trajectories. Recently, the study of cylindrical particle trajectories in roll-type corona electrostatic separators had been published [5]. However the research of factors which influenced the trajectories of

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doi:10.1016/j.jhazmat.2007.09.089

**Nomenclature**

| | |
|---|---|
| $a$ | acceleration of the particle (m/s$^2$) |
| $E$ | electric field strength (V/m) |
| $F_c$ | centrifugal force (N) |
| $F_e$ | electric force (N) |
| $F_g$ | gravity force (N) |
| $F_r$ | air drag force (N) |
| $L$ | minimum surface distance of rotating pole and electrostatic pole (m) |
| $n$ | rotation speed of rotating roll (rpm) |
| $r_0$ | radius of the particle (m) |
| $r_s$ | surface equivalent radius (m) |
| $R_1$ | radius of the rotating roll (m) |
| $R_2$ | radius of the electrostatic electrode (m) |
| $U$ | supplied high-voltage (V) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | included angle of horizontal line and electrodes center line (°) |
| $\theta_d$ | angle of the point particle detaching from rotating roll (°) |
| $\rho$ | mass density of the particle (kg/m$^3$) |

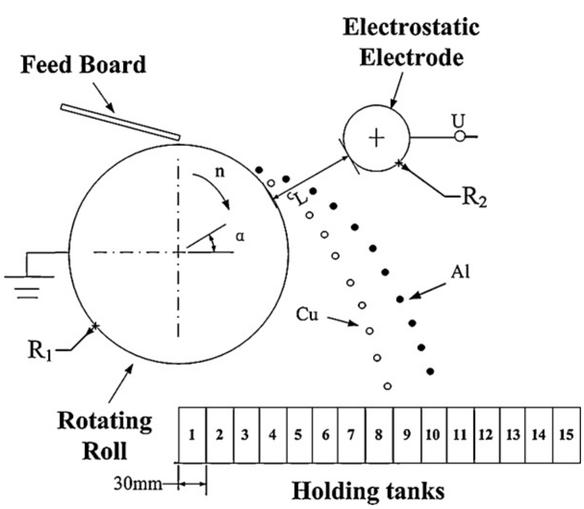


Fig. 1. Diagram of roll-type electrostatic separator.

conducting particles is not thorough enough. The trajectory of particle depends on the electrostatic separation system such as: electrical factors, mechanical factors and material factors. Consequently, the computer simulation method is a vital tool for the research and development of particle trajectory in RES.

## 3. Trajectories analysis

The theoretic model [4] has been established from computing electric field and the analysis of forces on the particles. However, some particles were acicular, filar or flat, not spherical and the charging value of the particle was correlated with it is surface area. Then, the surface equivalent radius ($r_s$) is used. The particle's $r_s$ is

$$r_s = \frac{\sqrt{S/\pi}}{3} \tag{1}$$

where $S$ is the surface area of particle.

As shown in Fig. 2, when the particle was acicular, the particle was regarded as ellipsoid and the $S$ is

$$S = 2\pi a^2(1 + FG) \tag{2}$$

where $F = A/(2\sqrt{A-1})$; $A = c^2/a^2$; $G = \pi/2 + \arcsin[(A-2)/A]$.

When the particle was filar or flat, the particle was regarded as cylinder and the $S$ is

$$S = 2\pi r^2 + 2\pi rh \tag{3}$$

From the theoretic model [4], the electric field strength ($E$) in the system of RES can be explained:

$$E_{(x,y)} = f_1(U, L, R_1, R_2, x, y),$$
$$E_{(\alpha)} = f_2(U, L, R_1, R_2, \alpha) \tag{4}$$

The degree of particle's detachment point ($\theta_d$) can be expressed from (4).

$$\theta_d = f_3(E_\theta, r_0, \rho, n), \qquad \theta_d = f_4(U, L, R_1, R_2, r_0, \rho, n) \tag{5}$$

As shown in Fig. 3, the collecting point can be computed from (4) and (5)

$$d = f_5(U, R_2, \alpha, R_1, n, H, r_0, \rho) \tag{6}$$

where "$U$, $R_2$ and α" are the electrical factors, "$R_1$, $n$ and $H$" the mechanical factors and "$r_0$ and $\rho$" are the material factors. All of these factors influenced the separating results of mixture metal particles.

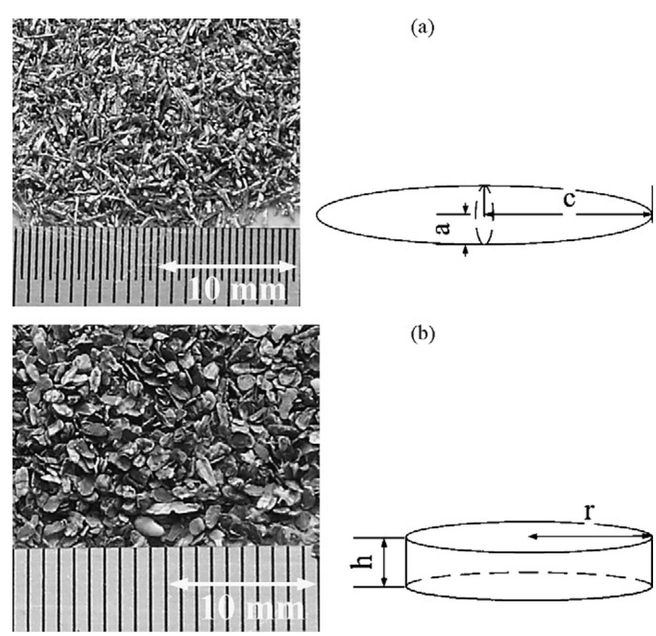


Fig. 2. The particle was treated as the model of ellipsoid (a) and cylinder (b).

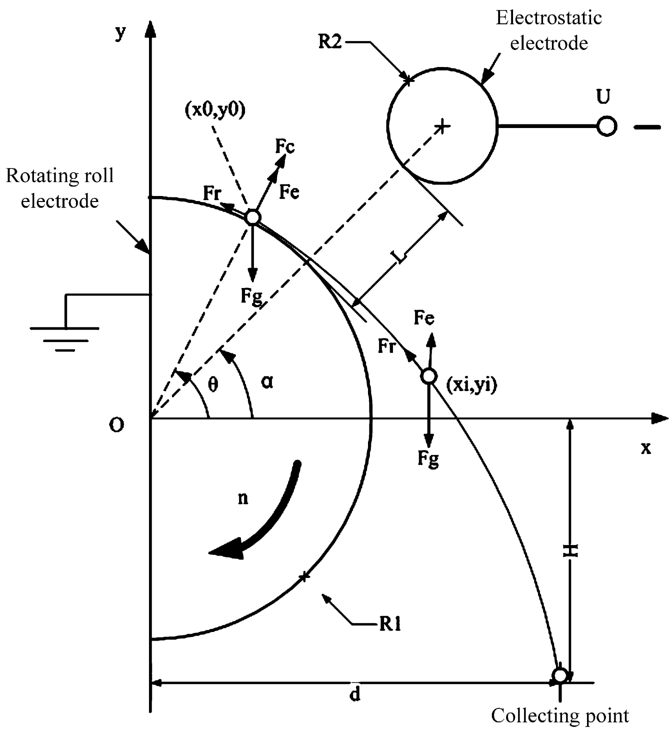


Fig. 3. Co-acting forces on a particle before leaving the rotating roll and after.

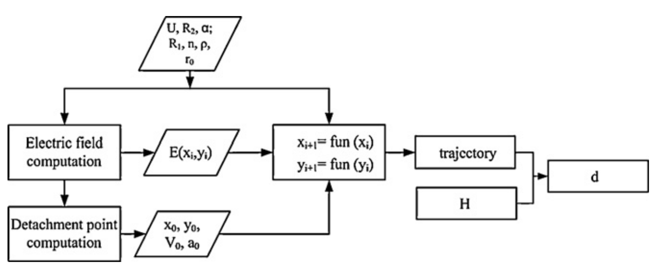


Fig. 4. Flow chart of the program for computing model.

The software of MATLAB is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numerical computation. A program written by MATLAB language was designed to compute Eq. (6), as shown in Fig. 4. At the first step, the electric field strength in the active zone of the separator was evaluated. Then the distribution of electric field and operating parameters were used to compute the particle trajectory in the air, after detachment. Finally, the collecting point was got. The operating parameters ($U$, $R_2$, $\alpha$, $R_1$, $r_0$, $\rho$, $n$, $H$) were the input data for the program. The collecting point ($d$) was the output data.

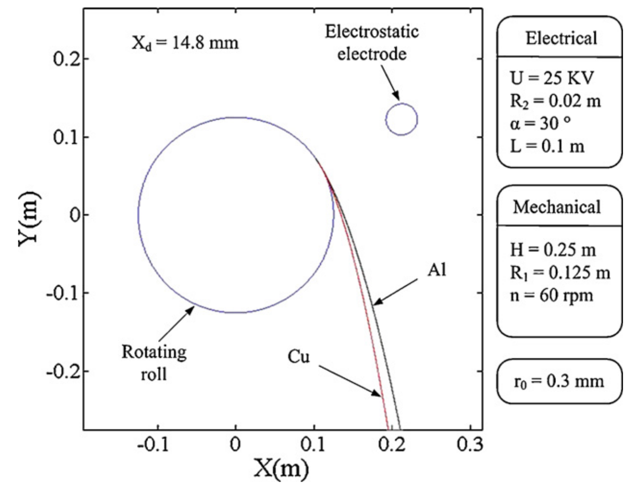


Fig. 5. Separating mixture metal particles (copper and aluminum) with RES in general operating parameter.

## 4. Results and discussion

Fig. 5 shows the particle trajectories of mixture material (copper and aluminum) in the RES with the general operating parameters. The difference between $d_{(\mathrm{Cu})}$ and $d_{(\mathrm{Al})}$ ($X_\mathrm{d}$) was only 14.8 mm. This distance barely supports industrial application. Single factor changing method was used to prove if a series optimized operating parameters could be applied in practical production. On the basis of general operating parameters, only one factor was changed and other factors were unchanged. In this study, each parameter changed in suitable range, as shown in Table 1. Fig. 6 shows the computing results of single factor changing method. The distance of collecting points between two different materials can be computed by the program. The operating parameters can be classified to three sorts: electrical, material and mechanical parameters.

### 4.1. Electrical parameters

The parameters $U$, $R_2$, $\alpha$ and $L$ were the electrical parameters for RES. As shown in Fig. 6(a), $X_\mathrm{d}$ was increased along with the elevation of applied voltage ($U$). The higher value of $U$ was good for separating, but it would be limited to 60 kV for saving the costing of direct current power in RES. As shown in Fig. 6(b) and (d), large electrostatic pole ($R_2$) and small L both increased the electric field strength in the active zone and enhanced the effect of electric force to the particle, so $X_\mathrm{d}$ was also increased. However, overlarge $R_2$ or over small $L$ could bring the collisions between particles and electrostatic pole and break

Table 1
Experimental parameters for simulation

| | Electrical factors | | | Material factor, $r_0$ (mm) | Mechanical factors | | | |
|---|---|---|---|---|---|---|---|---|
| | $U$ (kV) | $R_2$ (m) | $\alpha$ (°) | | $L$ (m) | $H$ (m) | $R_1$ (m) | $n$ (rpm) |
| Minimum | 15 | 0.01 | 0 | 0.2 | 0.05 | 0.15 | 0.1 | 1 |
| Maximum | 60 | 0.1 | 60 | 0.5 | 0.1 | 0.40 | 0.2 | 80 |
| Step | 1 | 0.001 | 1 | 0.05 | 0.002 | 0.01 | 0.005 | 1 |

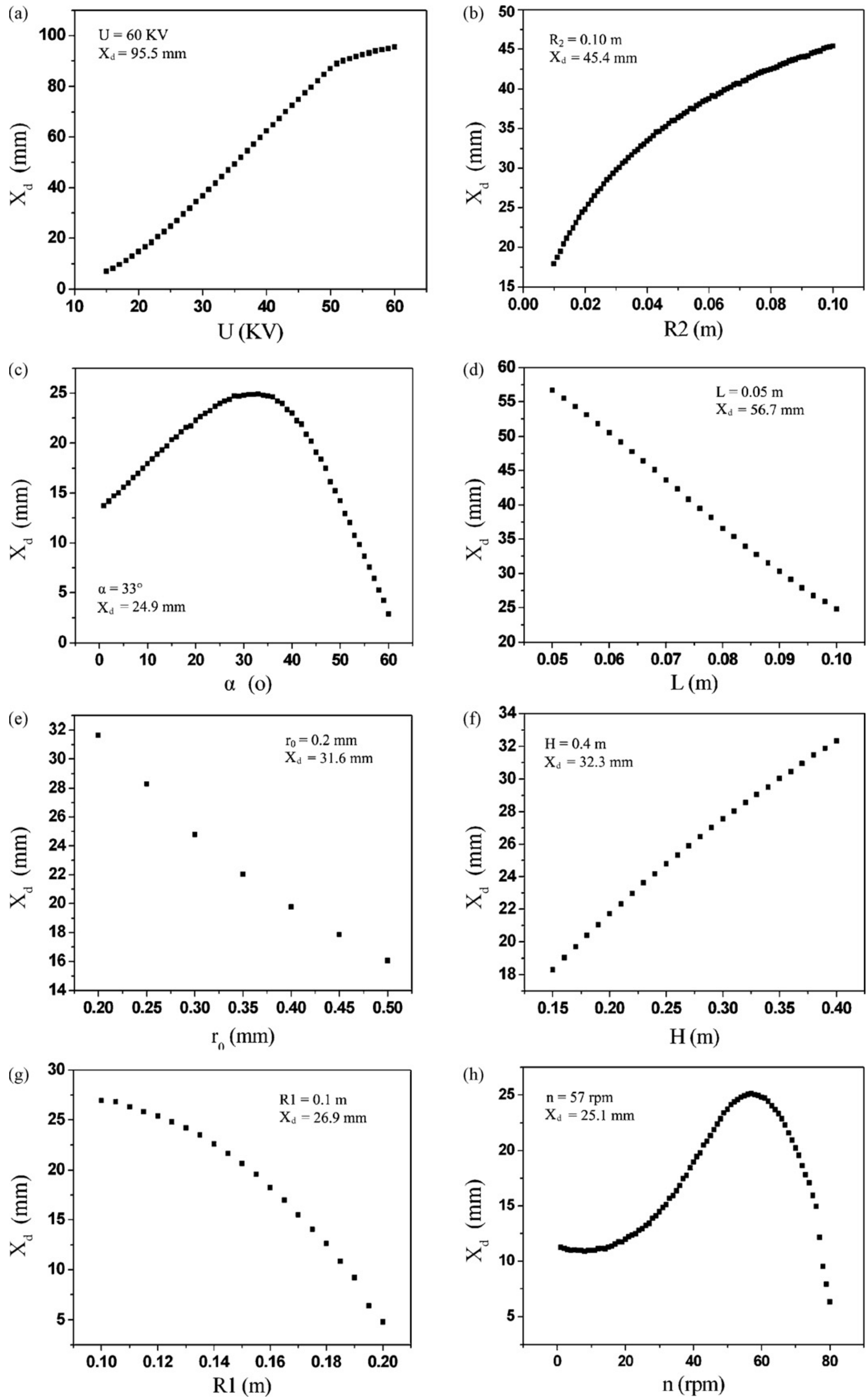


Fig. 6. Computing results of the $X_d$ variety by the single operating parameter: (a) $U$–$X_d$; (b) $R_2$–$X_d$; (c) $\alpha$–$X_d$; (d) $L$–$X_d$; (e) $r_0$–$X_d$; (f) $H$–$X_d$; (g) $R_1$–$X_d$; (h) $n$–$X_d$.

the natural particle trajectory. Then their values must be limited in suitable range. As shown in Fig. 6(c), when $\alpha$ was 33°, the $X_d$ got the maximum value. The variety of $\alpha$ changed the distribution of electric field strength in the active zone. When $\alpha < 33°$, the high-electric field strength zone closed to $x$-axis (Fig. 3), as shown in Eq. (5), the $\theta$ would be smaller and decreased the separating effect. When $\alpha > 33°$, the influence of electrostatic electrode to the particle was decreased, which caused bad separation.

### 4.2. Material parameters

As shown in Fig. 6(e), small particles were more suitable for separating, since the Fe had larger effect on small particles. But triboelectric charging effects and air flow had obvious impact to the motion of fine particles ($r_0 < 0.1$ mm) during separation. So the size of particle would not too small. The electric field force (Fe) had more effect to light metals than heavy metals [4]. So, the large density difference of different metals was favor for separation.

### 4.3. Mechanical parameters

Larger fall distance ($H$) extended the particles' flight space and improve the separating effect as shown in Fig. 6(f). So, the H should be large enough under the mechanical limitation of RES. As shown in Fig. 6(g), small rotating roll was good for separation. The rotating speed ($n$) had an optimal value, as shown in Fig. 6(h). As shown in Fig. 6(h), the rotating speed ($n$) had the maximum value when $n = 57$ rpm.

### 4.4. Optimizing operating parameters

Through the analysis of single factor changing method, the suitable operating parameters of RES was got. Simple combination of these operating parameters would make particles knock on the static electrode and the trajectories of particles were broke. So some of operating parameters were adjusted for avoiding the phenomena of impact and maximizing the $X_d$. As shown in Fig. 7, a set of optimized operating parameters which under the mechanical limitation of RES were used in separating copper and aluminum particles by the RES (Fig. 1). The size and position of electrodes changed great and a higher applied voltage was used. Under this set of optimized operating parameters, the results of simulation shows that the $X_d$ was 71.8 mm, which was about five times higher than the general operating parameters ($X_d = 14.8$ mm). Fig. 8 shows the experimental results by the RES under the optimized parameters. The particles of copper and alumina were screened by the electric vibrator. The copper particles mainly concentrated on the No. 9 holing tank and the aluminum particles mainly concentrated on the No. 11 holding tank. The width of each holding tank was $30 \pm 2$ mm. The experimental results show that the particle distance of copper and aluminum was about 65 mm which had a good agreement with simulation results. This computer simulating method could compute the relative operating parameters for separating other metal (tin, zinc, etc.) particles from waste PCBs. The new type

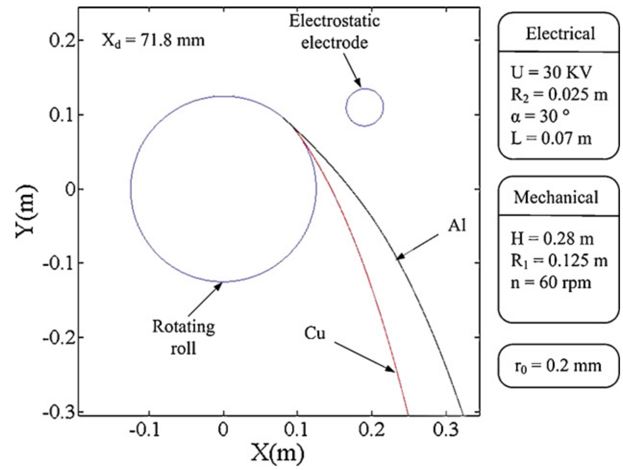


Fig. 7. Simulation results of optimized parameters for separating particles of copper and aluminum.

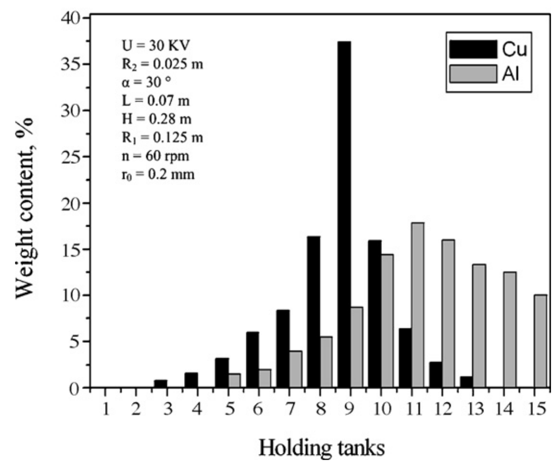


Fig. 8. Experiment results of optimized parameters for separating particles of copper and aluminum.

RES with bigger electrode and higher applied voltage was manufacturing. The results of other metals separating with new RES will be presented in a subsequent paper.

## 5. Conclusions

It has been shown in present study that, the collecting points of metal particles can be computed by Eq. (6). The impacts of electrical, material and mechanical factors to the particle trajectory were analyzed and the optimized operating parameters for separating copper and aluminum particles were got. The experimental results of separating copper and aluminum particles by roll-type electrostatic separator (RES) had a good agreement with computer simulation results, which proved the model could guide the RES to separate different metals from waste PCBs.

## Acknowledgements

This project was supported by the National High Technology Research and Development Program of China (863 program 2006AA06Z364), Program for New Century Excellent Talents in University and the Research Fund for the Doctoral Program of Higher Education (20060248058).

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