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An improved model for computing the trajectories of conductive particles in roll-type electrostatic separator for recycling metals from WEEE

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ABSTRACT

Electrostatic separation presents an effective and environmentally friendly way for recycling metals and nonmetals from ground waste electrical and electronic equipment (WEEE). For this process, the trajectory of conductive particle is significant and some models have been established. However, the results of previous researches are limited by some simplifying assumptions and lead to a notable discrepancy between the model prediction and the experimental results. In the present research, a roll-type corona-electrostatic separator and ground printed circuit board (PCB) wastes were used to investigate the trajectory of the conductive particle. Two factors, the air drag force and the different charging situation, were introduced into the improved model. Their effects were analyzed and an improved model for the theoretical trajectory of conductive particle was established. Compared with the previous one, the improved model shows a good agreement with the experimental results. It provides a positive guidance for designing of separator and makes a progress for recycling the metals and nonmetals from WEEE.

1. Introduction

With the sharp increase of the waste electric and electronic equipment (WEEE), the treatment of WEEE has become a very important subject. On one hand, the hazardous materials in WEEE may cause some environmental problems if there are no appropriate methods [1–3]. On another hand, WEEE is a rich resource because of its high content of noble metals and rare metals [4]. Therefore, the treatment of WEEE is significant not only for environmental protection, but also for resources recycle.

Electrostatic separation, defined as the selective sorting of charged or polarized bodies in an electric field [5–7], presents an effective and environmentally friendly way for recycling metals and nonmetals from WEEE. The roll-type corona-electrostatic separator is shown in Fig. 1. A grounded rotating roll electrode and other active electrodes (corona-electrostatic) connect to a DC high-voltage supply (negative polarity). The granular mixture to be separated is fed on the surface of the rotating roll with a certain speed, then pass through the electric field that generated between the roll electrode and active electrodes. After an intense "ion bombardment", nonconductive particles are charged and pinned to the surface of the rotating roll electrode by the electric image force while the conductive ones lose their charge to the grounded rotor and, thrown by centrifugal forces, are then attracted towards the electrostatic electrode [8].

From the principle of electrostatic separation, the key is the detachment of conductive particles from the granule mixture without the nonconductive particles. Therefore, the trajectory of conductive particle is significant for the quality of separation products [9,10]. Some numerical models for computing the trajectory of conductive particle in roll-type separator have been established [11–13]. Nevertheless, the results of these researches are limited by several simplifying assumptions. Fig. 2(a) shows a schematic representation for the previous models. The conductive particle is subjected only 2 forces, electric field force (F_q) and gravitational force (F_g), after detaching from the roll. In addition, the theoretical prediction is based on the assumption that all conductive particles are spherical and can acquire maximum charge. However, this is not true in practice. Firstly, the conductive particles move in a zone full of air and the air drag force (F_d) brings a significant impact on the actual trajectory, especially for the fine particles. Secondly, the charging situations are very different between the particles because of many factors, such as shape, size and other uncertain factors. In addition, the charge is also different even for the same particles. As a result, particles acquire different charge and most of them cannot reach the theoretical maximum charge.

The simplifying assumptions lead to a discrepancy between the model prediction and experimental results. Firstly, the fall-point of conductive particle calculated by the previous models is farther than practice. Secondly, the distribution zone of conductive products is much narrower than the experimental results. All of

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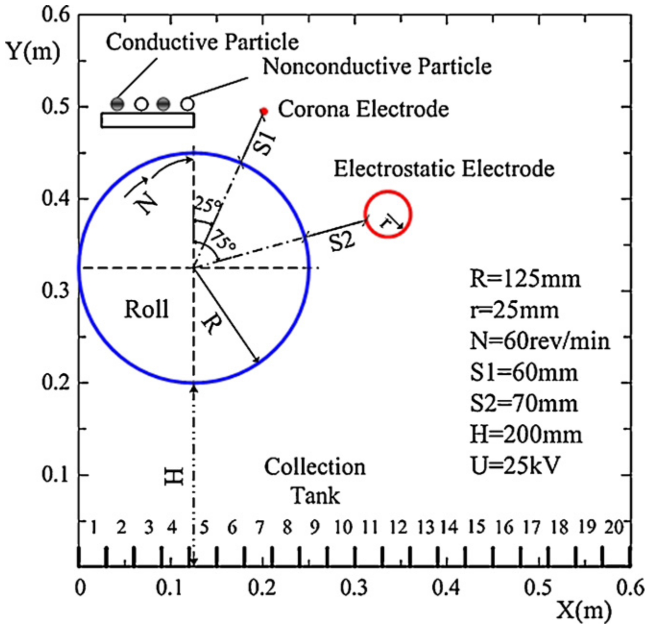

Fig. 1. Schematic representation of roll-type corona-electrostatic separator and its parameters.

these bring about a disadvantage for collecting the conductive products and middling products. Unfortunately, there is little published information that systematically discusses about these problems and the new model for improvements. The aim of present research is to take those factors ignored in previous models into account, to analyze their effects and establish an improved model for the theoretical trajectory of conductive particle in the roll electrostatic separator.

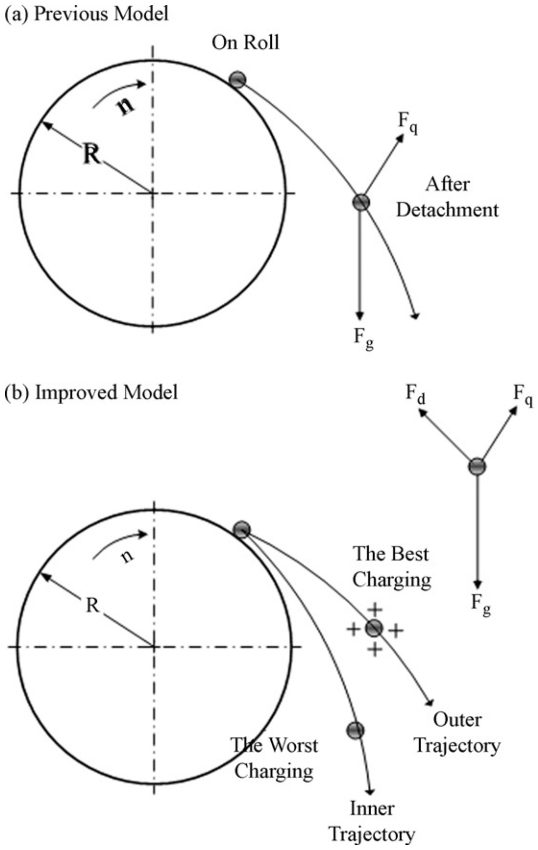

Fig. 2. Schematic representation of theoretical models. (a) Previous model; (b) improved model.

2. Improved theoretical modeling of particle trajectories

For the previous models, the conductive particle's movement is expressed by the following equations:

$$F_{qx} = m\gamma_x, \qquad F_{qy} - F_g = m\gamma_y \tag{1}$$

$$F_{qx} = E_x Q_m, \qquad F_{qy} = E_y Q_m \tag{2}$$

$$Q_m = 20.67\varepsilon E r^2 \tag{3}$$

where γ_x and γ_y are the x-component and y-component of acceleration, respectively. F_{qx} and F_{qy} are the x-component and y-component of F_q, respectively. E is the intensity of electric field. Q_m is the maximum charge acquired by particle. ε is the dielectric constant and r is the radius of particle.

Fig. 2(b) shows the schematic representation of improved model. The air drag force is introduced into the system. However, the charging situations are very complex and random, some reach the theoretical maximum and others are less than it. It is very difficult to describe the detail of such a complex situation. Fortunately, this problem can be settled by a simplification. Two critical curves, the outer trajectory and the inner trajectory are introduced to express the range of the trajectory family. The outer curve represents the smallest particles which moving under the best charging condition (acquire theoretical maximum charge). The inner one shows the motion of the largest particles under the worst charging condition (acquire zero charge and detach from the roll depend only by the centrifugal force).

The theoretical trajectory after improvement is expressed by the following equation:

$$F_{qx} - F_{dx} = m\gamma'_x, \qquad F_{qy} - F_g + F_{dy} = m\gamma'_y \tag{4}$$

where γ'_x and γ'_y are the x-component and y-component of acceleration, respectively,

and

$$F_{dx} = -6\pi\eta r\left(\frac{dx}{dt}\right) \quad \text{and} \quad F_{dy} = -6\pi\eta r\left(\frac{dy}{dt}\right) \tag{5}$$

where F_d is air drag force (Stokes's forces); F_{dx} and F_{dy} are the x-component and y-component of F_d, respectively; r is the particle radius; η is air drag coefficient, $1.81 \times 10^{-5}\,\mathrm{N\,s\,m^{-2}}$

3. Experimental setup

In the present research, ground printed circuit board (PCB) wastes were used as the test samples. For the PCB wastes, the extreme difference of density and electrical conductivity between metallic and nonmetallic materials provides an excellent condition for the application of the electrostatic separation [14]. In addition, the copper is the major metallic materials in the PCB wastes and it is always used as a representation of metals. Fig. 3 shows the test samples used in the research, 3 groups of copper particles, prepared by ground PCB wastes (I, 0.091–0.125 mm; II, 0.2–0.3 mm; III, 0.45–0.6 mm). Firstly, the numerical computation of their trajectories was performed according to the previous models and improved models, respectively. A simulation program, COMSOL Multiphysics3.2 (COMSOL Inc., Sweden) was used to simulate the electric field (Fig. 4) in the separator and calculate trajectories. Secondly, they were used to undergo a separation process in a roll-type separator for checking the trajectory compared with the numerical computation. Each group consists of 10 tests and each sample of

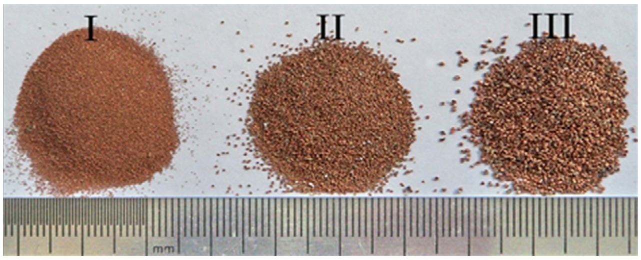

Fig. 3. Sample of conductive particles. Sample I 0.091–0.125 mm; sample II 0.2–0.3 mm; sample III 0.45–0.6 mm.

test was 100 g. The product of each test was collected in some tanks (width 0.03 m) and weighted by an electronic balance with resolution 0.1 g, respectively. All tests were carried out in ambient air, at a temperature of 20 °C and a relative humidity of 40–50%.

For a corona-electrostatic separation of such ground PCB wastes, there are many factors that influence the outcome. The preliminary experiments and a comprehensive discussion about these factors have been performed in previous researches [15,16] and the parameter settings that are used in the present paper are shown in Fig. 1.

4. Results

The numerical computing was performed according to Eqs. (1)–(5) and the foregoing critical charging situation. The theoretical trajectories of conductive particle are shown in Fig. 5. Obviously, there exist some notable differences between the previous model and the improved one. Firstly, the theoretical curves of improved model become closer to the roll. The fall-points of the improved trajectories displace towards the left compared with previous ones. The phenomenon is notable with the diminishment of particle size: the displacement is 0.01 m for group 3, 0.02 m for group 2 and 0.09 m for group 1, respectively. Secondly, the range of theoretical distribution zone becomes more extensive after improvement.

The distribution of the conductive particles in collection tanks are shown in Fig. 6. The comparison of distribution zone between the theoretical prediction and the experimental results is given in

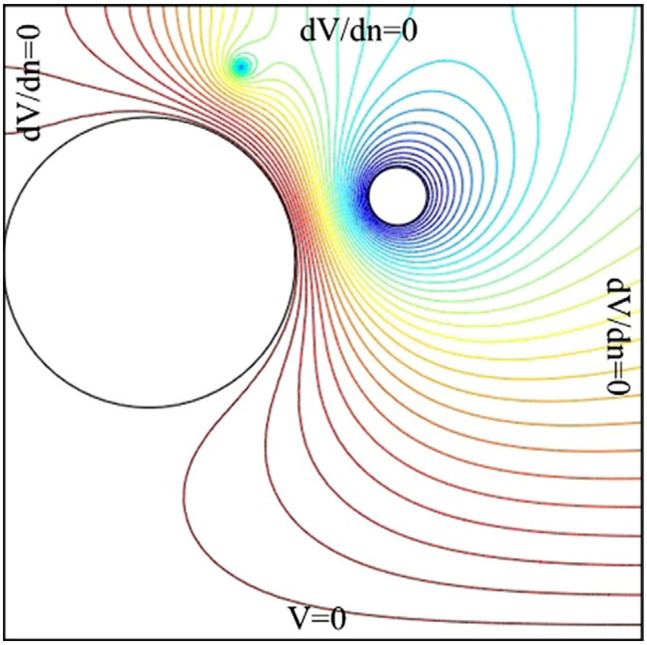

Fig. 4. The electric field in separator (equipotential lines computed by COMSOL Multiphysics3.2).

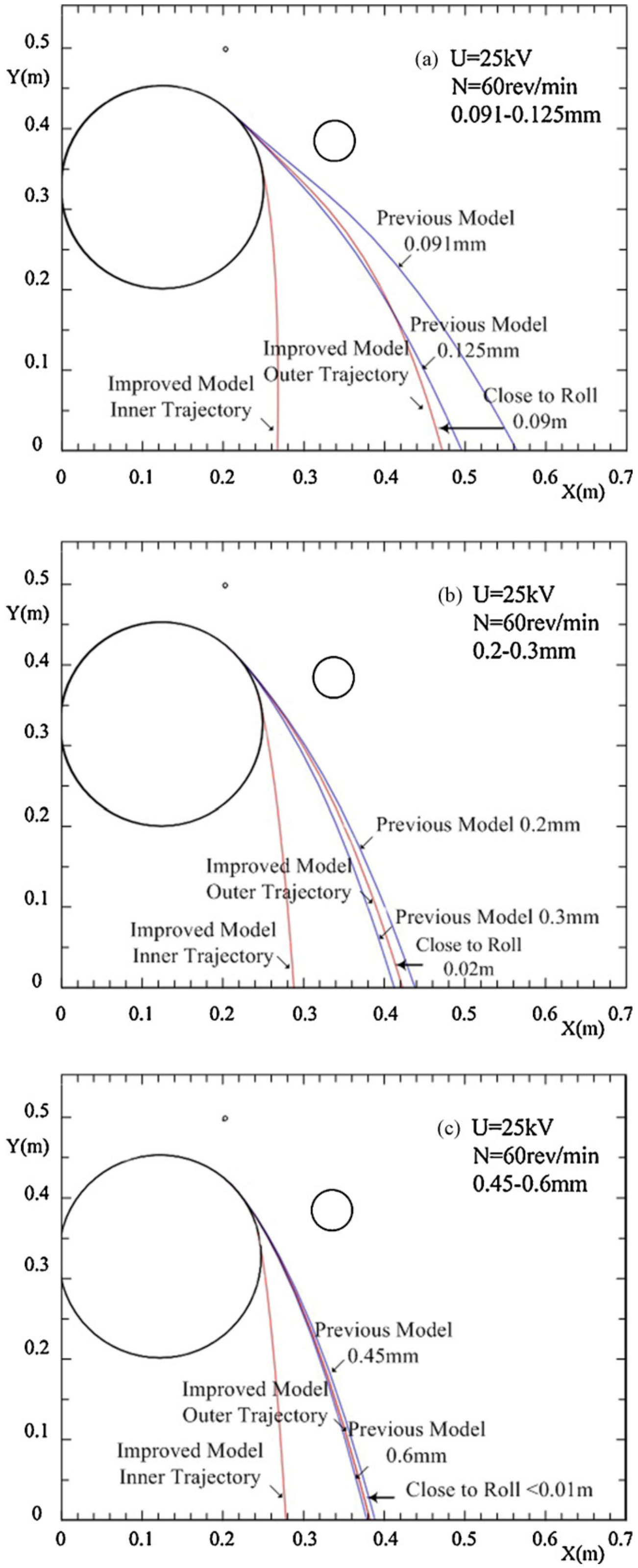

Fig. 5. Comparison of theoretical trajectories between previous model and improved model. (a) 0.091–0.125 mm; (b) 0.2–0.3 mm; (c) 0.45–0.6 mm.

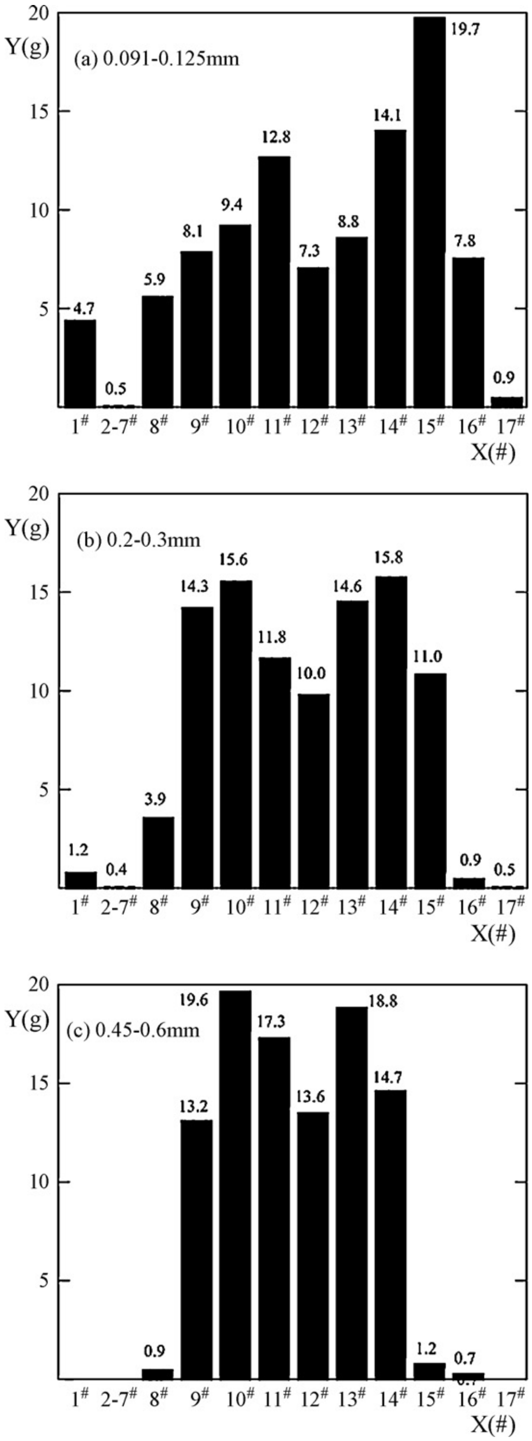

Fig. 6. Distribution of conductive particles in collection tanks. (a) 0.091–0.125 mm; (b) 0.2–0.3 mm; (c) 0.45–0.6 mm.

Fig. 7. Obviously, the improved model shows a good agreement with the actual distribution while the previous one has a considerable difference.

5. Discussion

The decrease of horizontal displacement of conductive particles was mainly influenced by the introduction of air drag force, especially for the fine particles. With the diminishment of particle size, the weight of the air drag force is greater. It means that the smaller the particle size, the greater the impact is. This is why the distribution zone of group 3 has the largest displacement (0.09 m) towards the roll. For the group 1 and 2, the influence of air drag force is not significant and both two theoretical models show a good agreement with experiment: the displacement is only 0.02 m for group 2 and <0.01 m for group 2, respectively. In practice, however, a few particles actually fall into the farther tanks, No. 16, 17 for group 2 and No. 15, 16 for group 3, respectively. The explanation is easy, a few particles fall into the destination tank, impact on its edge or bottom and finally bounce into the farther tank. The amount of these particles is very little and can be ignored. So the agreement is still good.

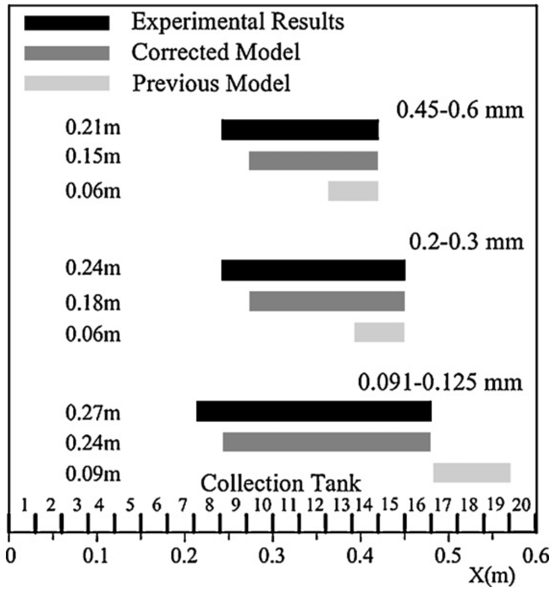

Fig. 7. Comparison of distribution zone between theoretical models and experimental results.

The expansion of distribution zone of conductive particles in collection tanks was mainly influenced by the different charging situation among particles. Compared with the previous model, there is a notable extension for the experiment and improved model. 0.27 and 0.24 m compared with 0.09 m for group 1, 0.24 and 0.18 m compared with 0.06 m for group 2 and 0.21 and 0.15 m compared with 0.06 m for group 3, respectively. The disagreement comes from the different charging situation of the conductive particles and Fig. 8 just shows the effect. Without the electric field, conductive particles form a clear, single and narrow trajectory. However, the particles in the electric field falling along a series of trajectories and form an unclear, multiple and wide family of trajectories. Considering the difference of the charging situation, the improved model makes a good agreement with the experimental data. The problem still exists, however, the inner trajectory cannot agree well with the experiments. For group 1, the inner curve predicts that the left limit for conductive particles is the tank No. 9. Nevertheless, the practical data show that particles can arrive in No. 5–8, even No. 1 (the non-conductive fraction of products). The similar situations take place in group 2 and 3. This phenomenon can be explained by the character of fine particles. The fine particle has a large specific area and intensive surface free energy. There exists some attractive forces (liquid bridge force, Van der Waals force) between them and lead the attractive effect. This makes the particles adhere to the roll, motion with it and fall in the tanks closer to left: No. 1–8 for group 1, No. 1–9 for group 2 and No. 8–9 for group 3, respectively. In addition, the smaller the size, the worse the phenomenon is. This is why there were considerable conductive particles collected in the

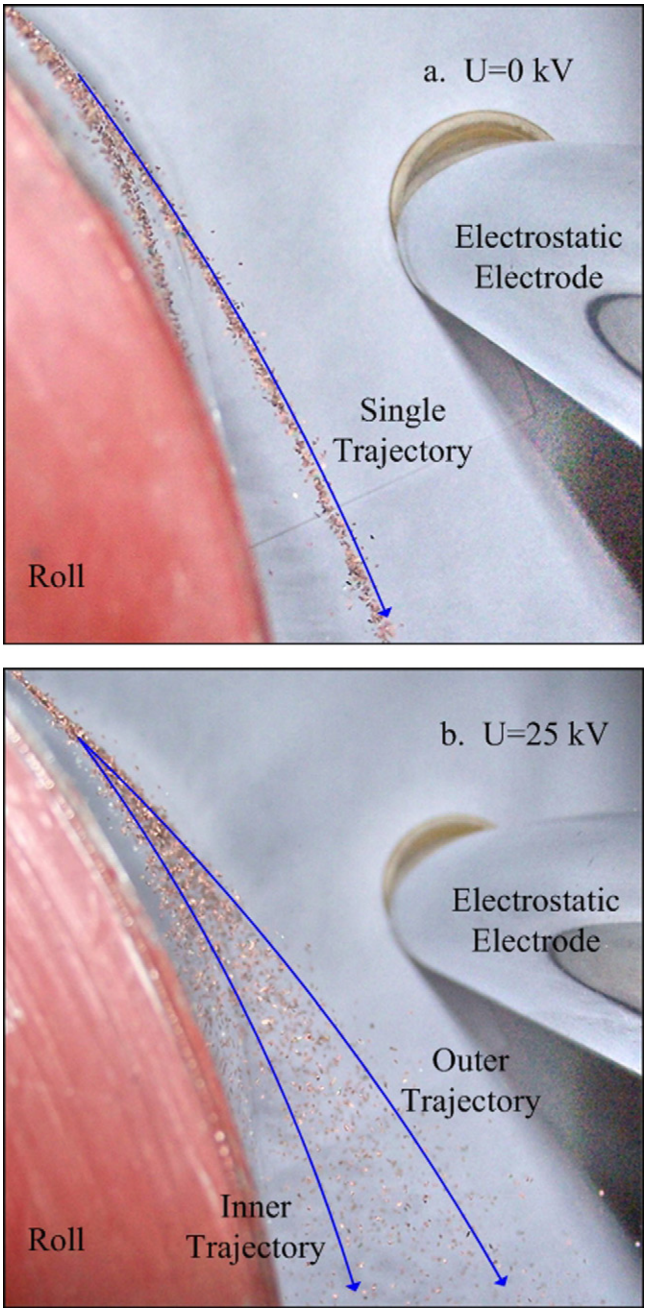

Fig. 8. Impact of high voltage on trajectory of conductive particle. (a) $U = 0$ kV; (b) $U = 25$ kV.

nonconductive fraction of products for group 1 (5.2 g) and group 2 (1.6 g).

6. Conclusion

(1) In the present research, two factors ignored in previous models, the air drag force and the different charging situation, were introduced into an improved model. These two factors lead notable impacts on trajectories of conductive particles in the electrostatic separator. The diminishment of horizontal displacement of conductive particles was mainly influenced by the introduction of air drag force, especially for the fine particles. The expansion of distribution zone of conductive particles in collection tanks was mainly influenced by the different charging situation among particles.

(2) By introducing these two factors into the previous model, an improved model for the theoretical trajectories of conductive particles in the roll electrostatic separator was established. Compared with the previous one, the corrected model showed a good agreement with the experimental results and made a progress for the electrostatic separation of the metals from the WEEE.

(3) In the present research, the sample is copper, the major metal in the PCB wastes. However, the improved model is applicable for the other metallic materials (stannum, zinc, etc.) in ground WEEE.

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