Electrostatic Separation of Chopped Waste Electric Cables*

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Abstract
In this paper, we present the results of experimental and analytical studies of the separation of a copper and polyvinylchloride (PVC) mixture using an electrostatic separator. The separator consists of a plate electrode and a conductive conveyor belt, and it can be inclined about two axes with respect to the horizontal plane. Copper and PVC particles obtained from chopped waste electric cables were used in this study. Separation tests were performed on a sample containing 50% PVC and 50% copper using this method. Prior to separation, the mixture is triboelectrically charged. The principle behind the separation technique is based on the difference in Coulomb force acting on the copper and PVC particles. It was found that the separation efficiency depends on parameters such as the triboelectric charging time and the slope of the conveyor belt. It was possible to obtain high purities and recovery rates of copper and PVC.

Key words: Electrostatic Separation, Recycling, Induction Charging, Triboelectric Charging, Coulomb Force

1. Introduction

Recently, new recycling laws for electrical products and automobiles have taken effect in Japan. Thus, it is desirable to increase their recycling rates. In particular, the recycling of electric cables, which are used in both products, is being watched closely monitored in Japan (1).

Most electric cables consist of copper and PVC. Therefore, separating them is one of the important steps in a system for recycling waste electric cables.

For the separation of waste electric cables, there are two types of separation methods, depending on the cable radius. In the case of electric cables with a large radius, copper is directly pulled out from the cables. In the case of electric cables with a small radius, they are chopped to liberate copper from their PVC coatings. Then, the granular copper and PVC mixture is separated.

For the separation, density-based separation and electrostatic separation have been widely used (2-8). A density-based separator has a simple construction. However, secondary pollution such as effluent is a source of apprehension because density-based separation utilizes liquid to obtain high separation efficiency. Electrostatic separation separates the mixture into copper and PVC due to the difference in the electrostatic force acting on the particles to be separated. In particular, most electrostatic separators which realize high separation efficiency utilize corona charging. Electrostatic separation has many advantages

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such as low energy consumption, high throughput and dry separation. However, it is necessary to devise a strategy for eliminating ozone, which is generated from corona electrodes.

In this paper, we present the results of experimental and analytical studies of the electrostatic separation of a copper and PVC mixture using induction and triboelectric charging. The separator consists of a plate electrode and a conductive conveyor belt, and it can be inclined about two axes with respect to the horizontal plane. Copper and PVC obtained from chopped waste electric cables were used in this study. This study was conducted to understand the effects of various parameters on separation efficiency and thereby determine the optimum operating conditions.

![Figure 1: Model of electrostatic separator](image)

2. Separation principle

Figure 1 shows a model of the electrostatic separator used in this study. The separator consists of a conductive conveyor belt with a plate electrode. The X-Y and the x-y planes are parallel to the horizontal plane and the conveyor belt, respectively. The conveyor is inclined at angles $\theta$ and $\alpha$ with respect to the X- and Y-axes, respectively. The angles $\theta$ and $\alpha$ are smaller than the angle of the static friction between the conveyor belt and the particles to be separated. The plate electrode, which is parallel to the conveyor belt, is fixed to the conveyor. The plate electrode is subjected to a constant negative voltage and the conveyor belt is grounded. Prior to separation, the copper and PVC mixture is charged in a triboelectric charging device. Then, copper and PVC particles become positively and negatively charged, respectively. When the negatively charged PVC particles are fed onto the conveyor belt through the feeder, the particles are attracted toward the conveyor belt due to the electrostatic force and are then conveyed along the conveyor belt. When the copper particles come in contact with the belt, the particles also become positively charged due to induction charging. The positively charged copper is attracted toward the plate electrode due to the electrostatic force and is repelled from the conveyor belt simultaneously. In this way, copper is separated from the PVC and copper mixture because of the difference in trajectories.

3. Analytical model

Figure 2 shows the forces acting on a particle on the conveyor belt. In this figure, the conveyor belt is gray. The equation of motion for a particle is given by
Fig. 2  Forces acting on charged particle

\[
m\ddot{x} = F_x - mg \sin \alpha \\
m\ddot{y} = F_y + mg \sin \theta \\
m\ddot{z} = R + F_c - F_g \\
F_g = mg \left( \tan^2 \alpha + \tan^2 \theta + 1 \right) 
\]

where \( m \) is the particle mass and \( g \) is the acceleration due to gravity, \( F_x \) and \( F_y \) are the \( x \)– and \( y \)–directional components of the frictional force acting on the particle, respectively. \( F_c \) and \( R \) are the Coulomb force and normal force acting on the particle, and the dots denote time derivatives.

The Coulomb force \( F_c \) for a particle is given by

\[
F_c = 1.369 \times 4\pi \times \sigma r^2 E^2 \quad \text{\cdots For Cu} \\
F_c = qE \quad \text{\cdots For PVC} 
\]

where \( r \) and \( \varepsilon \) are the particle radius and electric permittivity for air, respectively, \( q \) and \( E \) are the charge accumulated on the particle and the uniform electric field strength, respectively.

The frictional forces \( F_x \) and \( F_y \) are given by

\[
F_x = \mu R \frac{V - \ddot{x}}{u_R} \\
F_y = \mu R \frac{\ddot{y}}{u_R} 
\]
\[ u_R = \sqrt{(\dot{x} - V)^2 + \dot{y}^2} \]  

where \( \mu \) is the coefficient of friction between the particle and the conveyor belt, and \( u_R \) and \( V \) are the relative velocity of the particle with respect to the conveyor belt and the belt speed, respectively.

When the copper particle is conveyed along the belt, the particle velocity \( \dot{z} \) in the \( z \)-direction is equal to zero. Then, the normal force \( R \) is obtained from Eq. (6) from Eq. (1).

\[ R = F_g - F_c \]  

The copper particle on the conveyor belt becomes positively charged due to the induction charge, and the PVC particle becomes negatively charged due to the triboelectric charging. Therefore, the normal force \( R \) of the PVC particle is larger than that of the copper particle.

The behaviors of the PVC and copper particles can be calculated using Eqs. (1)-(6).

Figure 3 shows the trajectories of the PVC and copper particles obtained by the calculation. In this calculation, it is assumed that no triboelectric charging process was executed. \( \mu_t \) and \( \mu_c \) are the coefficients of friction between PVC and the conveyor belt, and between copper and the conveyor belt, respectively, and are identical to the conditions in an experiment, as discussed later. \( X_0 \) and \( Y_0 \) are the lengths of the conveyor belt in the \( x \) - and \( y \) -directions, respectively.

The initial condition is expressed as
\[ x = y = 0.005 \, (m) \]
\[ \dot{x} = V, \, \dot{y} = 0 \, (m/s) \]  

(7)

As shown in this figure, it is evident that the trajectory of the copper particle is different from that of the PVC particle. It is also clear that the slope \( \alpha \) results in an increase in the difference in trajectories. Therefore, the proposed method allows the separation of the copper and PVC mixture.

4. Experimental apparatus

An experiment was performed to verify the validity of the separation method.

Figure 4 shows the experimental apparatus used for separating the copper and PVC mixture. This separator consists of a plate electrode and a stainless-steel conveyor belt, and it can be inclined about two axes with respect to the horizontal plane. The collection system, consisting of 9 collecting trays, is attached to the separator, as shown in Fig. 5.

Figure 6 shows the copper and PVC particles used in this study. All particles were obtained from chopped waste electric cables. The radius of copper is about 0.04-0.07mm.

Figure 7 shows the logarithmic cumulative frequency distribution of particle mass. In this figure, the solid lines represent the cumulative probability of the logarithmic normal distribution. It is clear that the lines agree with the experimental trend. Therefore, the particle masses for copper and PVC exhibit of logarithmic normal distributions.
Figure 8 shows the mixer used for triboelectric charging. The mixer has a propeller with a diameter of 50mm. The mixture was charged in a polymethylmethacrylate (PMMA) cylinder with an interior diameter of 60mm. The reason why PMMA is used as the cylinder for triboelectric charging is as follows. Table 1 shows a triboelectric series for PVC, PMMA and copper. Any material higher in the table in contact with one lower in the table will charge negatively. Therefore, PVC and copper will be charge negatively and positively, respectively, upon coming in contact with each other or PMMA.

![Figure 8](image1)

(a) Charger  (b) Propeller

Fig. 8  Triboelectric charger

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Triboelectric series</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>negative charging</td>
</tr>
<tr>
<td>PMMA</td>
<td>↓</td>
</tr>
<tr>
<td>Copper</td>
<td>positive charging</td>
</tr>
</tbody>
</table>

![Table 1](image2)

The experiment was carried out as follows. Known amounts of copper and PVC (20 gram of each) were placed in the PMMA cylinder for triboelectric charging, as shown in Fig. 8. The charged copper and PVC particles were then fed into the separator, as shown in Fig. 4. The copper and PVC particles that fell into the each collection tray were retrieved and weighed.

![Figure 9](image3)

Fig. 9  Recovery rate in each collection tray for copper and PVC

\[ \theta = 10^\circ, \alpha = 6^\circ, E = 333kV/m, V = 202mm/s, T = 180\text{scc}, \omega = 720rpm \]

The experiment was carried out as follows. Known amounts of copper and PVC (20 gram of each) were placed in the PMMA cylinder for triboelectric charging, as shown in Fig. 8. The charged copper and PVC particles were then fed into the separator, as shown in Fig. 4. The copper and PVC particles that fell into the each collection tray were retrieved and weighed.
5. Experimental result

Separation efficiency can be evaluated on the basis of purity and recovery rate. These terms are defined as follows.

For PVC in tray A

\[
Purity = \frac{\text{Mass of PVC in tray A}}{\text{Total mass in tray A}}
\]

(8)

\[
\text{Recovery rate} = \frac{\text{Mass of PVC in tray A}}{\text{Total mass of feed material PVC}}
\]

(9)

For copper, the purity and recovery rate were calculated by replacing PVC with copper in Eqs. (8) and (9).

Figure 9 shows the amounts of copper and PVC recovered from each collection tray. \( T \) and \( \omega \) are the triboelectric charging time and rotating speed of the propeller for triboelectric charging, respectively. Most of the copper particles were collected in trays 1-3 and most of the PVC particles were collected in tray 9. It is clear, therefore, that copper particles can be separated from the copper and PVC mixture.

Figures 10 (a) and (b) show the effect of the slope \( \alpha \) on the amounts of PVC and copper recovered from each collection tray. As shown in Fig. 10 (a), it is clear that for the range of the slope \( \alpha \) used, the amounts of PVC in each collection tray are independent of \( \alpha \). The reason is that \( \alpha \) is smaller than the angle of the static friction between the PVC and the conveyor belt. The amount of copper in tray 1 increases as the slope \( \alpha \) increases. This is because the normal force \( R \) decreases with increasing slope \( \alpha \) as shown in Eq. (6). Also, the amount of copper in tray 2 reached a peak for \( \alpha = 6^\circ \). The reason is that tray
2 is the nearest one to the feeding point as shown Fig. 5.

Figures 11 (a) and (b) show the effect of the slope $\theta$ on the amounts of PVC and copper recovered from each collection tray. As in Fig. 11 (a), the amount of PVC in each collection tray is independent of the slope $\theta$. As the slope $\theta$ increases, the amount of copper in tray 1 increases. This is also because the normal force $R$ decreases with increasing slope $\theta$.

Fig. 11  Effect of slope $\theta$ on recovery rates in each collection tray for copper and PVC

\[
\begin{align*}
\alpha = 6^\circ, E = 367 \text{kV/m}, V = 121 \text{mm/s}, T = 0 \text{sec}, \omega = 0 \text{rpm}
\end{align*}
\]

Fig. 12  Effect of electric field strength on recovery rate in each collection tray for copper

\[
\begin{align*}
\theta = 10^\circ, \alpha = 6^\circ, V = 121 \text{mm/s}, T = 0 \text{sec}, \omega = 0 \text{rpm}
\end{align*}
\]

Figure 12 shows the effect of the electric field strength on the amount of copper recovered from each collection tray. As the electric field strength increases, the amount of...
copper recovered from tray 1 increases. The reason is that the electrostatic force increases with increasing electric field strength.

Figure 13 shows the belt speed against the amount of copper recovered from each collection tray. As the belt speed increases, the negative slope of the recovery rate to the collection tray number decreases slightly. The reason is that it is easy to convey the copper along the conveyor belt for large belt speed.

![Fig. 13](image)

**Fig. 13** Effect of belt speed on separation recovery rate in each collection tray for copper

\[(\theta = 10^\circ, \alpha = 6^\circ, E = 367 kV/m, T = 0 \text{ sec}, \omega = 0 \text{ rpm})\]

![Fig. 14](image)

**Fig. 14** Effect of triboelectric charging time on separation efficiency

\[(\theta = 10^\circ, \alpha = 6^\circ, E = 333 kV/m, V = 202 mm/s, \omega = 720 \text{ rpm})\]

<table>
<thead>
<tr>
<th>Purity</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>99.9 %</td>
</tr>
<tr>
<td>PVC</td>
<td>99.0 %</td>
</tr>
</tbody>
</table>

**Table 2** Best experimental result

After considering numerous experimental results, trays 1-3 and 9 were designated for the collection of copper and PVC, respectively.

Figure 14 shows the effect of the triboelectric charging time on the purity and recovery rate of copper. A dotted line and a chain line represent cases in which triboelectric charging was not executed. Triboelectric charging makes it possible to obtain high purity and recovery rate of copper. It is also clear that the recovery rate of copper increases as the
triboelectric charging time increases.

Table 2 shows the best result obtained in the experiment. It is possible to obtain high purity and recovery rate of copper and PVC.

6. Conclusions

The electrostatic separation of copper and PVC mixture was investigated both analytically and experimentally. The separator, which is inclined about two axes, consists of a conductive conveyor belt with a plate electrode. It was found that the triboelectric charging process makes it possible to obtain high purities and recovery rates of copper. It was also found that the separation efficiency depends on parameters such as the triboelectric charging time and the slope of the conveyor belt. It was possible to obtain high purities and recovery rates of copper and PVC.

References