Project Title: DEVELOPMENT OF NOVEL ROTARY TRIBOELECTROSTATIC SEPARATOR FOR DRY CLEANING OF PULVERIZED FINE COAL AT POWER PLANTS

ICCI Project Number: 08-1/4.1A-1
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ABSTRACT

Triboelectrostatic separation is a dry process based on the fact that particles can be charged differently upon friction or contact. It is widely used in mineral beneficiation, material purification, food processing, etc. Drawbacks of conventional triboelectrostatic separators are low throughput and poor efficiency, which limit their applications. In this project, a novel rotary triboelectrostatic separator has been developed to further clean Illinois coal after pulverization at the power plant to produce better quality coal with lower ash, mercury, and sulfur prior to combustion. After pulverization or size reduction, more ash and pyrite minerals are liberated from coal, providing an ideal feed to the rotary triboelectrostatic separator, which can effectively clean micronized fine coal particles without the need of water or any chemical reagents. The cleaned product can be directly fed to the boiler without further treatment, reducing the cost of post-treatment to meet stringent environmental air quality regulations.

The novel rotary triboelectrostatic separator is characterized by an innovative high efficiency rotary charger, charger electrification, laminar air flow, and specially designed electrodes. Experimental results have shown that, compared with conventional triboelectrostatic separators, the novel rotary triboelectrostatic separator can increase particle charge density, improve solids throughput, enhance process efficiency, and reduce overall energy consumption. Major operational parameters of the rotary triboelectrostatic separator that were investigated include feed rate, applied charger voltage, charger rotation speed, and air co-flow rate. Individual process variables have been optimized and their interactions determined from a multiple factor three level Box-Behnken statistical experimental design. It has been demonstrated that the rotary triboelectrostatic separator technology is effective in reducing ash, sulfur, and mercury, and its performance is comparable or better than the flotation release analysis with three of five coal samples tested.
EXECUTIVE SUMMARY

Run-of-mine coal often contains high levels of impurities such as ash, mercury, and sulfur that have to be removed before coal can be utilized by electric utility companies or the steel making industry. This process is referred to as coal cleaning, which is accomplished at the coal washing plant usually located at or near the coal mine. Most run-of-mine coal is cleaned by low-cost gravity and heavy medium separation processes in water with particles of up to several inches in size. However, it is well known that coal particles larger than even one millimeter still contain a significant amount of ash, mercury, and sulfur due to poor liberation of minerals. Thus, some of the “clean” coal product from the coal preparation plant is still considered to be non-compliance coal and requires blending with higher quality coal before combustion or utilization of expensive post-combustion cleaning processes to meet air emission standards. It should be pointed out that it is not feasible to reduce all coal particles to millimeters or micrometers at the coal preparation plant to produce cleaner coal since it will tremendously increase the cost of cleaning, dewatering, and transporting coal fines.

At power generation utility plants, coal is often pulverized to –200 mesh (75 µm) size prior to combustion. Pulverized coal has an average particle size of about 5 µm. At such a fine size, ash-forming minerals including mercury- and sulfur-containing pyrite are essentially liberated from the coal matrix in Illinois coal. Thus, pulverized coal provides an ideal feed to the dry triboelectrostatic separation process to further upgrade the coal by removing additional ash, mercury, and sulfur. Unfortunately, this approach has not been adopted by the utility industry due to lack of a high-throughput and cost-effective triboelectrostatic separator.

The present project was conducted to develop a patent-pending novel rotary triboelectrostatic separator (RTS) for dry cleaning of Illinois coal after pulverization at the power plant to further reduce ash, mercury, and sulfur content in coal, thus significantly expanding the market for and increasing the value of Illinois coal. The cleaned product can be directly fed to the boiler without further treatment. The RTS is characterized by an innovative high efficiency rotary charger, charger electrification, laminar air flow, and specially designed electrodes. Experimental tests have shown that, compared with a conventional separator, the innovative separator has increased particle charge density, improved solids throughput, enhanced process efficiency, and reduced overall energy consumption. The RTS technology provides an efficient dry separation process for cleaning or purification of coal fines and other fine particles.

Experimental tests with five coal samples have demonstrated excellent separation performance. For example, a clean coal of 5% ash was obtained from a pulverized fine coal with 8% feed ash at a combustible recovery of more than 80%. With a coarse coal sample, the proposed technology reduced the ash from about 16% to 11% at a combustible recovery of more than 79%, which is far better than other dry separation processes. In contrast, a froth flotation process failed to produce a clean coal with less than 11.5% ash; it could only produce a clean coal of 12% ash at a combustible recovery of only about 38%, which is far inferior to the proposed technology.
OBJECTIVES

The overall goal of this project was to develop the innovative rotary triboelectrostatic separation (RTS) technology to clean pulverized Illinois fine coal at the power plant to further upgrade the coal by removing additional ash, mercury, and sulfur. Major efforts were directed at converting non-compliance Illinois coal to compliance coal. The specific objectives of the proposed project included:

1. Fabricate and modify as necessary a laboratory prototype separator with a capacity of 30 lb/h of –200 mesh pulverized coal;
2. Evaluation of the prototype system for design features and performance limits;
3. Parametric investigation of the proposed technology to understand effects of process variables on separation performance with four typical Illinois coal samples;
4. Optimization of process variables using a multiple factor three level Box-Behnken statistical experimental design;
5. Economic evaluation of the proposed technology.

INTRODUCTION AND BACKGROUND

Triboelectrostatic separation is a dry separation process based on the fact that when two particles are rubbed against each other, the particle with higher work function becomes negatively charged and the other positively charged. (Carta et al., 1976; Lockhart, 1984; Alfano et al., 1988). The work function, $\Phi$, is defined as the minimum energy supplied to extract an electron from a solid. It is a measure of how tightly electrons are bound to a material. Charged particles are subsequently separated in an external electric field as a result of their different motion trajectories.

A separation zone shown in Figure 1 can be used to describe moving particle trajectories in an electric field where $x$ represents the horizontal direction and $y$ the vertical direction. When a charged particle enters the electric field, its trajectory is governed by the momentum of the gas flow and gravity in addition to the electric force. It deflects to a positive or negative electrode, depending on its charge polarity.

If high voltage electrodes are mounted vertically as shown in Figure 1, the electrostatic force will accelerate particles horizontally. The particle residence time, i.e., the time for particle travel through the separation chamber, is controlled by the particle’s vertical motion. However, the horizontal particle motion is controlled by electric field deflection. The law governing the horizontal displacement, $\bar{x}$, of the moving particle is:
\[
\frac{d^2 \vec{x}}{dt^2} = \vec{E}(\frac{q}{m}) \tag{1}
\]

where \( m \) is particle mass, \( \vec{x} \) is horizontal displacement vector, \( t \) is time, \( \vec{E} \) is electric field intensity, and \( q \) is particle charge. The charge-to-mass ratio, \( q/m \), is referred to as particle specific charge. It is a very important parameter for the motion of the particle in the electrostatic separation process.

If the resistance of air with viscosity, \( \eta \), is also considered, the horizontal motion of a moving spherical particle of radius, \( r \), is given by:

\[
\frac{d^2 \vec{x}}{dt^2} + 6\pi \eta \frac{r}{m} \frac{d\vec{x}}{dt} = \vec{E}(\frac{q}{m}) \tag{2}
\]

The solution to Equation (2) gives the speed of the particle as a function of time:

\[
\frac{d\vec{x}}{dt} = \frac{\vec{E}q}{6\pi \eta r}(1 - e^{-\frac{t}{m/6\pi \eta r}}) \tag{3}
\]

When \( t \gg \frac{m}{6\pi \eta r} \) or \( t \to \infty \), the terminal horizontal speed of the particle is:

\[
\left(\frac{d\vec{x}}{dt}\right)_{\text{horizontal}} = \frac{\vec{E}q}{6\pi \eta r} \tag{4}
\]

Under these conditions, the terminal horizontal speed is independent of the mass. However, since time, \( t \), is in the range of milliseconds, mass plays an important role in determining the horizontal motion of the particle, and therefore the resultant trajectory which affects separation performance.

Particle motion in the vertical direction is influenced by gravitational force and gas drag force. The governing equation is:

\[
\frac{d^2 y}{dt^2} = 6\pi \eta \frac{\eta}{m} \frac{dy}{dt} + g \tag{5}
\]

where \( \eta \) is the dynamic viscosity of gas and \( g \) is the gravitational acceleration.

For the initial conditions of \( t = 0, y(0) = 0, \) and \( dy(0)/dt = V_0 \), Equation (5) can be solved as

\[
y(t) = \frac{(g + V_0)B}{B^2} e^{Bt} - Bg t - g - V_0 \frac{B}{B^2} \tag{6}
\]

where \( B = 6\pi r \frac{\eta}{m} \).
Particle trajectories can be obtained from Equations (4) and (6) under given conditions. Figure 2 shows typical trajectories for negatively charged particles of different sizes. They deflect right to the positive electrode and can be readily separated from positively charged metal particles which deflect left to the negative electrode.

The particle trajectory is affected by particle charge, mass, and radius, and by electric field intensity, as indicated in Equations (4) and (6). A larger difference in trajectories of different type particles enhances separation efficiency. This may be achieved by use of higher electric field intensity and greater particle charge density. However, the electric field intensity is limited by air ionization and is normally set at 300,000–500,000 V/m. A potentially major improvement in separation efficiency can be achieved by enhancing particle charge density, which is the advantage of RTS technology.

The separation or cleaning of –100 mesh (–150 µm) fine coal particles is difficult and inefficient due to their very small mass, large surface area, and high surface energy. It is often accomplished using wet methods such as froth flotation and occasionally selective agglomeration that explore the difference in surface properties of different components in the presence of chemical reagents. However, wet methods have several major disadvantages including addition of chemical reagents, discharging and impounding tailing slurry, and high cost of product dewatering. Froth flotation is the most widely used wet separation process for fine particles. However, its high process efficiency is limited to a very narrow particle size range, which is usually 10–100 µm. Moreover, there are many applications where wet cleaning methods are not feasible. A good example is the cleaning of pulverized coal at the power plant. Illinois coals are well liberated at sizes smaller than 1 mm. Coal-fired power plants normally pulverize coal to about 80% below –200 mesh or 0.075 mm. If an efficient dry separation process is available for fine particles, further cleaning of this pulverized coal to remove additional ash and sulfur can be accomplished prior to combustion at the power plant, significantly lowering ash and sulfur content in coal and reducing flue gas scrubbing costs.

The coal and utility industries prefer dry coal cleaning processes to wet ones due to flowsheet simplicity, lower capital and operating costs, etc. of dry cleaning processes. Triboelectrostatic separator is the most promising dry separation process for fine particles. However, existing dry triboelectrostatic separators have not found wide application in the mining industry due to relatively poor separation efficiency, low throughput, narrow
particle size range, etc. All these problems can be overcome by introducing the proposed technology with an innovative design and better control of aerodynamics in the charging and separation chambers of the separator.

The electrostatic charger is the most critical component of triboelectrostatic separation technology. It has the greatest impact on the technical performance of the separator. Typical conventional triboelectrostatic chargers include the honeycomb, in-line mixer, tubing, cyclone, and mesh belt; most of them having a common feature that the charger is stationary while particles have to be conveyed in low concentrations by a large volume of air at a speed of up to 10–20 m/s to produce a turbulent flow and create sufficient particle-to-particle collisions or particle-to-wall collisions for particle charging, which consumes tremendous amounts of energy and requires high operating and maintenance costs. The high air velocity reduces the retention time of particles in the separation zone or the electrical field, reducing the separation performance of the triboelectrostatic separator. The mesh belt charger is different from other types of chargers, and it relies on a moving belt to render particles charged. The mesh belt charger has several major drawbacks including high maintenance cost, low separation efficiency, poor performance for coarse particles that severely limit its applications. Due to their low separation efficiency and high energy and maintenance costs, conventional triboelectrostatic separation technologies have found few commercial applications. It is of great economic and environmental importance to develop an innovative high efficiency triboelectrostatic separation technology for pulverized fine coal cleaning.

EXPERIMENTAL PROCEDURES

Laboratory Prototype RTS Separator

A continuous laboratory prototype separator illustrated in Figure 3 was fabricated for pulverized fine coal cleaning. Rotary chargers made of stainless steel and copper were used for fine coal cleaning. An electrical potential was applied to the rotating charger via a copper brush which was connected to the charger via a unique mechanism. The particle transport pipe and vacuum pumps were also improved. The modified separator has an overall dimension of 6” (L) × 3” (W) × 50” (H) and a capacity of approximately 30 lb/h. The rotary charger has dimensions of about 3” in diameter and 4” in length.

The rotary triboelectrostatic separation system includes a vibratory sample feeder, a rotary charger or charge exchanger, a separation chamber, an injection gas unit, and two high voltage DC supplies. Samples are fed by the feeder into the rotary charger. A small amount of transport gas is injected with the feed. Gas-particle flow interacts with the rotary charger. Due to particle-to-charger or particle-to-particle collisions, particles become charged negatively or positively, depending on their work functions. Charged particles then pass through the separation chamber and report to one of three cyclones attached to the system. A honeycomb collimator was used to minimize turbulence and vibration electrodes were deployed to reduce particle deposition in the separation chamber. One of the two high voltage sources in the system is for particle charging and is attached to the rotary charger. The other is for the separation of charged particles and is attached to the separation chamber.
Figure 3. The laboratory triboelectrostatic separation system.

Fine Coal Samples

A total of five pulverized coal samples were acquired; three from Southern Illinois Power Cooperative (SIPC) and two from Ameren Energy. The three SIPC coal samples were labeled International Resources (SIPC#1), Royal Falcon (SIPC#2), and ILB; the two Ameren Energy samples were labeled Labadie Unit 4 (Ameren#1) and PRB U100 (Ameren#2). Proximate analysis results for all five coal samples are shown in Table 1. As can been seen, Ameren#1, Ameren#2, and ILB coal samples have significantly higher volatile matter but much lower ash content than SIPC#1 and SIPC#2 coal samples. The particle size distribution of all five coal samples was measured using the wet screening method and results are shown in Tables 2–6.

Table 1. Proximate analysis results of coal samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Moisture (%)</th>
<th>Volatile Matter (%)</th>
<th>Ash (%)</th>
<th>Fixed Carbon (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIPC#1</td>
<td>16.44</td>
<td>32.41</td>
<td>23.93</td>
<td>27.22</td>
</tr>
<tr>
<td>SIPC#2</td>
<td>8.96</td>
<td>28.35</td>
<td>31.91</td>
<td>30.78</td>
</tr>
<tr>
<td>ILB</td>
<td>11.41</td>
<td>38.07</td>
<td>10.39</td>
<td>40.13</td>
</tr>
<tr>
<td>Ameren#1</td>
<td>16.32</td>
<td>45.50</td>
<td>7.45</td>
<td>30.73</td>
</tr>
<tr>
<td>Ameren#2</td>
<td>15.49</td>
<td>45.77</td>
<td>7.04</td>
<td>31.70</td>
</tr>
</tbody>
</table>
Table 2. Size analysis data for SIPC#1 coal sample.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Wt (%)</th>
<th>Ash (%)</th>
<th>Cumulative Underscreen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wt (%)</td>
</tr>
<tr>
<td>2.38</td>
<td>15.55</td>
<td>15.98</td>
<td>100.00</td>
</tr>
<tr>
<td>2.38-1.19</td>
<td>12.09</td>
<td>13.78</td>
<td>84.45</td>
</tr>
<tr>
<td>1.19-0.595</td>
<td>12.67</td>
<td>11.69</td>
<td>72.36</td>
</tr>
<tr>
<td>0.595-0.250</td>
<td>18.43</td>
<td>9.68</td>
<td>59.69</td>
</tr>
<tr>
<td>0.250-0.125</td>
<td>11.46</td>
<td>12.33</td>
<td>41.26</td>
</tr>
<tr>
<td>0.125-0.074</td>
<td>5.74</td>
<td>15.15</td>
<td>29.80</td>
</tr>
<tr>
<td>0.074-0.044</td>
<td>4.48</td>
<td>19.96</td>
<td>24.06</td>
</tr>
<tr>
<td>-0.044</td>
<td>19.58</td>
<td>52.17</td>
<td>19.58</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>20.81</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Table 3. Size analysis data for SIPC#2 coal sample.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Wt (%)</th>
<th>Ash (%)</th>
<th>Cumulative Underscreen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wt (%)</td>
</tr>
<tr>
<td>2.38</td>
<td>26.90</td>
<td>18.60</td>
<td>100.00</td>
</tr>
<tr>
<td>2.38-1.19</td>
<td>15.27</td>
<td>15.22</td>
<td>73.10</td>
</tr>
<tr>
<td>1.19-0.595</td>
<td>12.00</td>
<td>19.90</td>
<td>57.84</td>
</tr>
<tr>
<td>0.595-0.250</td>
<td>10.99</td>
<td>24.03</td>
<td>45.84</td>
</tr>
<tr>
<td>0.250-0.125</td>
<td>5.86</td>
<td>29.42</td>
<td>34.84</td>
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<tr>
<td>0.125-0.074</td>
<td>3.65</td>
<td>34.26</td>
<td>28.99</td>
</tr>
<tr>
<td>0.074-0.044</td>
<td>2.55</td>
<td>37.99</td>
<td>25.33</td>
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<tr>
<td>-0.044</td>
<td>22.78</td>
<td>66.81</td>
<td>22.78</td>
</tr>
<tr>
<td>Total</td>
<td>26.90</td>
<td>18.60</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Table 4. Size analysis data for ILB coal sample.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Wt (%)</th>
<th>Ash (%)</th>
<th>Cumulative Underscreen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wt (%)</td>
</tr>
<tr>
<td>2.38</td>
<td>35.37</td>
<td>7.86</td>
<td>100.00</td>
</tr>
<tr>
<td>2.38-1.19</td>
<td>22.22</td>
<td>8.80</td>
<td>64.63</td>
</tr>
<tr>
<td>1.19-0.595</td>
<td>27.14</td>
<td>10.61</td>
<td>42.41</td>
</tr>
<tr>
<td>0.595-0.250</td>
<td>2.01</td>
<td>11.76</td>
<td>15.28</td>
</tr>
<tr>
<td>0.250-0.125</td>
<td>5.46</td>
<td>12.21</td>
<td>13.27</td>
</tr>
<tr>
<td>0.125-0.074</td>
<td>2.66</td>
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<td>7.81</td>
</tr>
<tr>
<td>0.074-0.044</td>
<td>5.15</td>
<td>25.09</td>
<td>5.15</td>
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<tr>
<td>-0.044</td>
<td>100.00</td>
<td>10.24</td>
<td>100.00</td>
</tr>
<tr>
<td>Total</td>
<td>35.37</td>
<td>7.86</td>
<td>64.63</td>
</tr>
</tbody>
</table>
Table 5. Size analysis data for Ameren Energy#1 coal sample.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Wt (%)</th>
<th>Ash (%)</th>
<th>Cumulative Underscreen</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Wt (%)</td>
<td>Ash (%)</td>
<td></td>
</tr>
<tr>
<td>0.125</td>
<td>1.83</td>
<td>6.53</td>
<td>100.00</td>
</tr>
<tr>
<td>0.125-0.088</td>
<td>10.21</td>
<td>5.57</td>
<td>98.17</td>
</tr>
<tr>
<td>0.088-0.074</td>
<td>3.19</td>
<td>6.44</td>
<td>87.96</td>
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<tr>
<td>0.074-0.044</td>
<td>6.63</td>
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<td>84.76</td>
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<tr>
<td>0.044-0.037</td>
<td>19.37</td>
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<td>78.13</td>
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<td>0.037-0.025</td>
<td>8.35</td>
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<td>50.41</td>
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<td>Total</td>
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Table 6. Size analysis data for Ameren Energy#2 coal sample.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Wt (%)</th>
<th>Ash (%)</th>
<th>Cumulative Underscreen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wt (%)</td>
<td>Ash (%)</td>
<td></td>
</tr>
<tr>
<td>0.125</td>
<td>2.11</td>
<td>5.95</td>
<td>100.00</td>
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<tr>
<td>0.125-0.088</td>
<td>3.87</td>
<td>5.39</td>
<td>97.89</td>
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<tr>
<td>0.088-0.074</td>
<td>3.48</td>
<td>5.51</td>
<td>94.02</td>
</tr>
<tr>
<td>0.074-0.044</td>
<td>12.12</td>
<td>5.75</td>
<td>90.54</td>
</tr>
<tr>
<td>0.044-0.037</td>
<td>6.56</td>
<td>5.75</td>
<td>78.42</td>
</tr>
<tr>
<td>0.037-0.025</td>
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<td>6.29</td>
<td>71.86</td>
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<td>-0.025</td>
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<td>8.61</td>
<td>63.94</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td></td>
<td>0.00</td>
</tr>
</tbody>
</table>

Parametric Investigation of RTS Technology

A systematic parametric investigation of the proposed RTS separation technology was conducted for separation performance evaluation for SPIC#1, SPIC#2, Ameren#1, and Ameren#2 coal samples. All samples were kept in an oven to minimize moisture absorption. Up to 100 grams was processed in each experiment with feed metering provided by the action of a vibratory feeder. Three products were collected from the first stage; namely R (concentrate), C (middling), and L (tailing). Typically, a two-stage processing protocol was used. Each product from the first stage was further processed to generate nine final products. Unless otherwise specified, all separation tests were conducted using the copper charger, and under the following conditions: charger rotation speed: 3000 rpm; injection air velocity: 2.5 m/s; co-flow air velocity: 3.1 m/s; feed rate: 800 g/h; separation voltage: 22.5 kV; charger voltage: –2.5 kV; temperature: 24 °C.

Process parameters including feed rate (0.4, 0.8, 1.2, 2.0, and 3.6 kg/h), charger material (copper and stainless steel), charger rotation speed (2000, 3000, 4000, and 5000 rpm), applied charger voltage (–5, –2.5, 0, +2.5, and +5 KV), injection air flow velocity (0.9, 1.5, 2.5, 3.7, and 4.9 m/s), and co-flow rate (0.9, 1.5, 2.5, 3.7, and 4.9 m/s), were examined. All
samples were analyzed for ash content. Coal samples generated under optimum conditions were also analyzed for sulfur and mercury content, which were then used to determine ash, sulfur, and mercury rejection as well as combustible recovery for the process.

**Optimization of Process Variables**

To optimize individual process variables and evaluate their interactions, RTS separation of ILB Illinois coal sample (–7 to +325 mesh) was evaluated using a Box-Behnken experimental design. High- and low-levels (+1 and –1) of parameters such as feed rate, charger rotation speed, applied charger voltage, co-flow rate were determined based on parametric experimental results. Using response surface methodology (RSM), the most significant variables and optimum conditions were established from statistical analysis of the experimental results. The Box-Behnken experimental design and subsequent RSM analysis were conducted using sophisticated software Design-Expert 5.09 acquired from Stat-Ease Inc., Minneapolis, MN.

According to the Box-Behnken experimental design, optimal conditions were estimated using a second or a third order polynomial function to generate a correlation between studied factors and responses. The general form of the second order function is:

\[
E(y) = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{ij} x_i x_j + \sum_{i=1}^{3} \beta_{ii} x_i^2
\]

where: \(E(y)\) is the predicted response, \(X_i\) and \(X_j\) are studied variables, and \(\beta\) is an equation constant and coefficient.

Analysis of variance (ANOVA) was used to estimate statistical parameters. The extent of fitting experimental results to the polynomial model equation was expressed by the determination coefficient, \(R^2\). F-test was used to estimate the significance of all terms in the polynomial equation within a 95% confidence interval.

**RESULTS AND DISCUSSION**

There are many factors which affect the efficiency of triboelectrostatic separation, including material properties and operational parameters. The operational parameters such as feed rate, charger material, charger rotation speed, applied charger voltage, injection air flow velocity, and co-flow rate were evaluated to maximize coal beneficiation. All experimental results were from two stages of separation unless specified otherwise. In the following discussion, the coal rich product is referred to as concentrate and the ash rich product refers to as tailings.

The separation performance data in the following discussions is presented in terms of combustible recovery vs. products ash or normalized product ash which is defined as the percentage of product ash to feed ash. The normalized product ash is preferred in this study since the wet and sticky feed samples were very difficult to homogenize. Also, significant fluctuations in feed ash were observed in the tests.
Parametric Investigation of Separation

Effect of Feed Rate

Figures 4–7 show the effect of feed rate on the –7 mesh fraction of SIPC#1 and SIPC#2, as well as Ameren#1 and Ameren#2 coal samples, respectively. These results were normalized with respect to feed ash so that the shift in grade vs. recovery curves can be solely attributed to changes in feed rate. The curve that is closer to the upper left corner represents a better separation. Figures 6 and 7 show that higher feed rate lowered separation efficiency and the best feed rate for Ameren coal samples was 400-800 g/h, which was a result of fewer particle contacts with the charger surface and thus lower charge density on particle surfaces. However, the best separation was achieved at a moderately high feed rate of 2000 g/h with SPIC#1 and SPIC#2 coal samples, as shown in Figures 4 and 5. This suggests that with SPIC#1 and SPIC#2 coal samples, particle-particle contacts played a more significant role in particle charging than with Ameren coal samples. It should be noted that during these tests, concentrate moved toward the negative electrode and tailings were deflected to the positive electrode, suggesting that carbon particles were positively charged and minerals were negatively charged.

Figure 4. Feed rate effect on separation efficiency for SIPC#1 (–7 mesh).

Figure 5. Feed rate effect on separation efficiency for SIPC#2 (–7 mesh).
Effect of Charger Rotation Speed

Tribocharging is dependent on the relative motion speed between particles and the rotary charger, with higher speed resulting in stronger electrification. The easiest way to control this is to adjust the rotary charger rotation speed. Figures 8–11 show the effect of charger rotation speed for the −7 mesh fraction of SIPC#1 and SIPC#2, as well as Ameren#1 and Ameren#2 coal samples. At 5000 rpm, ash content can be reduced by 20% at a combustible recovery of about 60% for SIPC samples and approximately 70% for Ameren samples. This cleaning effect is considered to be significant since the feed was very fine coal that had been cleaned by traditional coal washing techniques with remaining ash components in middling particles known to be difficult to clean. This data clearly show that better separation was accomplished at higher rotation speeds of 4000 or 5000 rpm, which is consistent with established theory that higher surface charge results when relative motion speed between charger and particles increases. A higher rotary charger speed wears the roller more quickly. Therefore, the optimum charger rotation speed is 5000 rpm.
Figure 8. Charger rotation speed effect on separation efficiency for SIPC#1 (–7 mesh).

Figure 9. Charger rotation speed effect on separation efficiency for SIPC#2 (–7 mesh).

Figure 10. Charger rotation speed effect on separation efficiency for Ameren#1.
Effect of Applied Charger Voltage

One of the unique features of the rotary triboelectrostatic separator is the applied potential to the charger to enhance the particle charging process. Figures 12–15 show separation efficiency curves at different charging voltages ranging from –5 kV to +5 kV. It is quite clear from these figures that separation performance significantly increased as charging voltage varied from +5 kV to –5 kV, and compared to 0 V or no charging voltage, which is the case with conventional triboelectrostatic separation, the separation at –5 kV was substantially more efficient. For example, in Figure 14, a product ash reduction of 30% could hardly be obtained at 0 V charging voltage. However, it can be easily obtained at –5 kV charging potential with a combustible recovery of more than 55%. Comparing separation curves at 0 V and –5 kV suggests that up to 50% increase in combustible recovery was achieved if the charging voltage was changed from 0 V to –5 kV, which clearly illustrates the utmost importance of controlling the applied charger potential.

![Graph](image1)

**Figure 11.** Charger rotation speed effect on separation efficiency for Ameren#2.

**Figure 12.** Applied charger voltage effect on separation efficiency for SIPC#1 (–7+325 mesh).
Figure 13. Applied charger voltage effect on separation efficiency for SIPC#2 (–7+325 mesh).

Figure 14. Applied charger voltage effect on separation efficiency for Ameren#1.

Figure 15. Applied charger voltage effect on separation efficiency for Ameren#2.
Effect of Injection Air Flow Rate

It is known that injection air flow rate or velocity affects particle speed and residence time in both charging and separation chambers and thus, particle charge density and separation efficiency. At 3.1 m/s air co-flow rate, a higher injection air flow rate results in a faster velocity at which particles strike the charger but it causes shorter charging and separation times and hence, a lower separation efficiency. Figures 16–19 show separation efficiency curves at different injection flow velocities. For relatively coarse particles (−7+325 mesh) shown in Figures 16 and 17, separation efficiency was better at lower injection flow rates than at higher injection flow rates. This was possibly a result of shorter residence time in the separation chamber at higher air flow rates. For fine particles shown in Figures 18 and 19, the best separation performance was obtained at about 2.5–3.7 m/s injection air velocity, which was approximately equal to the co-flow velocity of 3.1 m/s. It is believed that air turbulence in the separation chamber was minimized when injection velocity and co-flow velocity were the same. A velocity lower than 2.5 m/s or higher than 3.7 m/s resulted in lower impact velocity for charging and shorter residence time for separation, respectively. It also increased air turbulence in the separation chamber, which is known to be detrimental for separation.

Figure 16. Injection flow rate effect on separation efficiency for SIPC#1 (−7+325 mesh).
Figure 17. Injection flow rate effect on separation efficiency for SIPC#3 (−7+325 mesh).

Figure 18. Injection flow rate effect on separation efficiency for Ameren#1.

Figure 19. Injection flow rate effect on separation efficiency for Ameren#2.
Effect of Air Co-Flow Rate

The gas flow that enters the separation zone on both sides of the connector between charging and separation chambers is referred to as co-flow. It is used to comb misplaced particles and force them to deflect to the desired product stream. Compared to current triboelectrostatic separators on the market, this is another distinct feature of the new rotary triboelectrostatic separator. Figures 20 and 21 show separation efficiency curves at different co-flow rates for SIPC#1 coal and Ameren#1 coal, respectively. Injection flow rate was kept equal to co-flow rate. With SIPC#1 coal, the separation curve moved consistently toward the upper left corner as the air co-flow rate increased from 1.5 m/s to 3.1 m/s, indicating that better separation was achieved at higher co-flow rates. As the co-flow rate further increased to 3.7 m/s, the separation curve shifted substantially toward the lower right corner, suggesting a poorer separation performance. Thus, the optimum co-flow rate for this coal sample was 3.1 m/s. Similar behavior was observed in Figure 21 with the Ameren#1 coal sample where the optimum air co-flow rate was 2.5 m/s. Comparing results in Figures 20 and 21 indicates that separation of Ameren#1 coal was less adversely affected by higher air co-flow rates since separation curves at 2.5, 3.1, and 3.7 m/s were fairly close to each other but all considerably better than at 1.5 m/s. Results shown in Figures 20 and 21 are consistent with previous studies on fly ash samples demonstrating that optimum performance is achieved when injection air flow and air co-flow rates are nearly equal to each other (Tao et al., 2008). It is believed that when two gas velocities are identical, turbulence in the separation chamber is minimal, which creates a favorable condition for efficient particle separation.

![Figure 20](image.png)

**Figure 20.** Co-flow rate effect on separation efficiency for SIPC#1 (−7+325 mesh).
Effect of Charger Material

Two chargers, one made of copper and one made of stainless steel, were tested for fine coal cleaning to investigate the effect of charger material on triboelectrostatic separation performance. Copper is known to be a good material for the charger while stainless steel is a common wear-resistant material. Figures 22–25 show separation efficiency curves obtained with both copper and stainless steel chargers. Obviously, the copper charger produced better separation than the stainless steel charger. The improvement in separation efficiency observed with the copper charger is more significant with the SIPC#1 coal, as shown in Figure 22. Apparently, the importance of the charger material for the separation efficiency depends on the coal sample to be processed.

![Figure 21. Co-flow rate effect on separation efficiency for Ameren#1.](image1)

![Figure 22. Charger material effect on separation efficiency for SIPC#1 (–7 mesh).](image2)
Figure 23. Charger material effect on separation efficiency for SIPC#2 (−7 mesh).

Figure 24. Charger material effect on separation efficiency for Ameren#1.

Figure 25. Charger material effect on separation efficiency for Ameren#2.
Optimization of Process Variables

Effect of Triboelectrostatic Separation Variables for ILB Coal Sample on Normalized Product Ash

Three-dimensional (3D) response surface plots that demonstrate the effect of different variables on normalized product ash content are depicted in Figures 26(a–f) for the ILB coal sample. These figures show 3D response surface plots of normalized ash content of three cumulative low ash products as a function of two RTS variables. The other two variables were held at center levels except charging voltage, which was kept at –5 kV when not being varied.

Figure 26a shows the effect of feed rate and applied charger voltage at center levels of charger rotation speed and air co-flow rate. Figure 26b shows the effect of charger rotation speed and feed rate at the center level of air co-flow rate and –5 kV applied charger voltage. Figure 26c shows the effect of feed rate and air co-flow rate at the center level of charger rotation speed and –5 kV applied charger voltage. Figure 26d shows the effect of applied charger voltage and charger rotation speed at center levels of feed rate and air co-flow rate. Figure 26e shows the effect of applied charger voltage and air co-flow rate at center levels of feed rate and charger rotation speed. Figure 26f shows the effect of charger rotation speed and air co-flow rate at the center level of feed rate and –5 kV applied charger voltage.

It is quite clear from Figures 26(a, b, c) that, as feed rate increased, normalized product ash increased; thus, the best product was obtained at low feed rates. Figures 26(a, d, e) show that, at lower feed rates, lower charger rotation speeds, or lower air co-flow rates, changing the applied charger voltage from 0 kV to +5 or –5 kV decreased normalized product ash. Figures 26(b, d, f) indicate that, as charger rotation speed increased, the normalized product ash became higher. Increasing air co-flow rate increased the normalized product ash, as shown in Figure 26(c, e, f).

From these experimental results, the third-order response function representing normalized product ash content of clean coal was determined to be a function of feed rate (A in g/h), applied charger voltage (B in kV), charger rotation speed (C in rpm), and air co-flow rate (D in m/s). The following equation shows the relationship between the response and these coded variables:

\[
\text{Product ash/feed ash} = + 80.04 + 2.01A + 1.43B - 4.03C - 1.60D - 3.60A^2 \\
+ 1.39B^2 + 1.54C^2 + 0.94D^2 + 0.79AB + 1.50AC + \\
2.29AD - 1.17BC + 1.03BD + 4.04AB^2 + 1.40AD^2 \\
+ 6.99B^2C
\]
Figure 26. Response surface plots showing effects of two out of four variables on normalized cumulative ash content for three lower ash coal samples. The other two variables were held at center levels except charging voltage, which was kept at –5 kV when not being varied. (a) Rotation speed and co-flow rate; (b) Charging voltage and co-flow rate; (c) Charging voltage and rotation speed; (d) Feed rate and co-flow rate; (e) Rotation speed and feed rate; (f) Charging voltage and feed rate.
Effect of Triboelectrostatic Separation Variables on Combustible Recovery

Three-dimensional (3D) response surface plots that demonstrate the effect of different variables on combustible recovery are depicted in Figures 27(a–f) for three cumulative low ash samples. These figures show 3D response surface plots of combustible recovery as a function of two RTS variables. The other two variables were held at center levels except charging voltage, which was kept at –5 kV when not being varied.

Figure 27a shows the effect of feed rate and applied charger voltage at center levels of charger rotation speed and air co-flow rate. Figure 27b shows the effect of charger rotation speed and feed rate at the center level of air co-flow rate and –5 kV applied charger voltage. Figure 27c shows the effect of feed rate and air co-flow rate at the center level of charger rotation speed and –5 kV applied charger voltage. Figure 27d shows the effect of applied charger voltage and charger rotation speed at center levels of feed rate and air co-flow rate. Figure 27e shows the effect of applied charger voltage and air co-flow rate at center levels of feed rate and charger rotation speed. Figure 27f shows the effect of rotation speed and air co-flow rate at the center level of feed rate and –5 kV applied charger voltage.

It is quite clear from Figures 27(a, b, c) that, as feed rate increased, combustible recovery increased slightly. Changing the applied charger voltage from 0 kV to +5 or –5 kV gave rise to a higher combustible recovery, which is shown in Figures 27(a, d, e). As charger rotation speed increased, combustible recovery increased, except at the high level of feed rate as shown in Figures 27(b, d, f). An increase in the air co-flow rate slightly increased combustible recovery as shown in Figure 27(c, e, f).

Similar to normalized product ash content, the third-order response function for combustible recovery of clean coal can be expressed as a function of feed rate (A in g/h), applied charger voltage (B in kV), charger rotation speed (C in rpm), and air co-flow rate (D in m/s) as follows:

\[
\text{Combustible recovery} = +15.25 - 4.23A + 0.25B - 1.81C - 3.01D + 7.76A^2 + 16.66B^2 + 4.18C^2 + 5.36D^2 + 4.50AB - 0.95AC + 0.06AD - 1.11BC + 4.95BD + 1.69CD - 4.10A^2D + 7.21AB^2 + 5.86B^2C - 2.31BC^2
\]

The optimum conditions listed in Table 7 were obtained using the sophisticated software Design-Expert 5.09® acquired from Stat-Ease Inc., Minneapolis, MN.
Figure 27. Response surface plots showing effects of two out of four variables on combustible recovery for three cumulative low ash products. The other two variables were held at center levels except charging voltage, which was kept at -5 kV when not being varied. (a) Rotation speed and co-flow rate; (b) Charging voltage and co-flow rate; (c) Charging voltage and rotation speed; (d) Feed rate and co-flow rate; (e) Rotation speed and feed rate; (f) Charging voltage and feed rate.
Table 7. Optimum conditions for ILB coal samples.

<table>
<thead>
<tr>
<th>No.</th>
<th>Feed Rate (g/h)</th>
<th>Charging Voltage (kV)</th>
<th>Rotation Speed (rpm)</th>
<th>Co-flow Rate (m/s)</th>
<th>Prod. Ash/FeedAsh</th>
<th>Comb. Rec.</th>
<th>Ash Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>408</td>
<td>-5</td>
<td>4714</td>
<td>3.18</td>
<td>72.43</td>
<td>48.86</td>
<td>63.94</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>-5</td>
<td>4173</td>
<td>3.61</td>
<td>69.60</td>
<td>41.05</td>
<td>68.83</td>
</tr>
</tbody>
</table>

Comparison of RTS Performance with Release Analysis

Release analysis was used to provide a measure of ultimate separability of a sample by froth flotation technique. Its result represents the best possible separation that can be achieved by froth flotation under ideal conditions. Figures 28–32 show release analysis and RTS separation results of SPIC#1, SPIC#2, ILB, Ameren#1, and Ameren#2, respectively. RTS performance was comparable to or considerably better than release analysis results for SIPC#1, Ameren#1, and Ameren#2, but was inferior to release analysis results for SPIC#2 and ILB coal samples.

The experimental program provided a broad range of a normalized product ash values as shown in Figure 28–32. While recovering 60% of combustible material, the RTS separator provided a reduction in ash content by about 40%, 20%, 20%, 27%, and 28% for SPIC#1, SPIC#2, ILB, Ameren#1, and Ameren#2 samples, respectively. These separation performances are significantly higher than the theoretical best performance predicted for froth flotation (release analysis data) except for SPIC#2 and ILB coal samples. However, simplicity and low cost characteristics of the RTS compared to other alternatives may override its inferior performance.

Figure 28. Release analysis and RTS separation performance for SPIC#1 (–7+325 mesh).
Figure 29. Release analysis and RTS separation performance for SPIC#2 (–7+325 mesh).

Figure 30. Release analysis and RTS separation performance for ILB (–7+325 mesh).

Figure 31. Release analysis and RTS separation performance for Ameren#1.
Ash, Sulfur, and Mercury Rejection

Ash, sulfur, and mercury separation efficiency under optimum operating conditions of the RTS separator for the –7+325 mesh fractions of SIPC#1, SIPC#2, and ILB, as well as Ameren#1 and Ameren#2 coal samples are shown in Figures 33–37, respectively. These figures show that sulfur and mercury rejection correlates well with ash rejection. The RTS technology is effective in reducing the amount of sulfur and mercury although ash is the easiest to remove for all coal samples except the ILB sample. For both SIPC coal samples, sulfur rejection was almost the same as Hg rejection. For the ILB coal sample, sulfur showed the highest rejection at a given product ash whereas Hg was most difficult to reduce. For the two Ameren coal samples, sulfur rejection was the lowest, possibly because it had the highest organic sulfur content.

Figure 32. Release analysis and RTS separation performance for Ameren#2.

Figure 33. Comparison of ash, sulfur, and mercury rejection efficiency of the RTS process for SIPC#1 (–7+325 mesh).
Figure 34. Comparison of ash, sulfur, and mercury rejection efficiency of the RTS process for SIPC#2 coal sample (–7+325 mesh).

Figure 35. Comparison of ash, sulfur, and mercury rejection efficiency of the RTS process for ILB coal sample (–7+325 mesh).
Figure 36. Comparison of ash, sulfur, and mercury rejection efficiency of the RTS process for Ameren#1 coal sample.

Figure 37. Comparison of ash, sulfur and mercury rejection efficiency of the RTS process for Ameren#2 coal sample.
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. For coal samples evaluated in this study, coal particles were positively charged while ash particles were negatively charged. Experimental results with them have demonstrated the excellent separation performance of the RTS process. For example, one stage of RTS separation can reduce ash by 13% at 90% combustible recovery with Ameren#2 coal sample. The RTS separation performance was comparable to or better than flotation release analysis with three of five coal samples tested.

2. Process variables including feed rate, injection air flow rate, air co-flow rate, and applied charger potential all affected separation efficiency. The appropriate applied charger potential was critical for separation efficiency. For tested coal samples, –5kV produced much better separation than 0 V or positive voltages. Injection flow rate and co-flow rate should be approximately equal to achieve the most favorable flow condition in the separation chamber. Optimum operating conditions for tested coal samples were 2000 g/h feed rate, 5000 rpm charger rotation speed, –5 kV charger potential, injection and co-flow air rates of approximately 2.5–3 m/s.

3. The copper rotary charger performed better than the stainless steel rotary charger in upgrading fine coal particles. The degree of improvement by the copper charger depends on the coal sample.

4. The RTS process has shown it can not only reduce ash content in the coal but also reject sulfur and mercury effectively, although sulfur and mercury were more difficult to remove from coal.

Recommendation

1. It is recommended that future work be conducted at a pilot-scale to verify performance data obtained in this study with the lab-scale RTS unit. This work should be designed to achieve more reliable engineering data for the development of scale-up criteria for the technology prior to its eventual commercialization in the coal industry.
REFERENCES


DISCLAIMER STATEMENT

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