REPORT
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ELECTROSTATIC DESULFURIZATION OF ILLINOIS COAL
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ABSTRACT

During the three years under the sponsorship of the Department of Energy and Natural Resources of the State of Illinois and the Coal Development Board we have invented several new, energy efficient techniques to continuously remove iron pyrites from Illinois Coal. One apparatus consists of a fluidized bed with perforated electrodes. Finely ground coal is fed into the fluidized bed and is split into two streams that leave through the perforated electrodes producing a clean coal stream and a pyrite enriched stream. To help us improve the process we have developed a mathematical model for separating pyrites in electrofluidized beds and conveyors and measured the surface charge of coal and pyrites as a function of humidity.

Since the fluidized bed was found to be restricted to coals ground to no less than 70 μm and since Illinois coals need to be ground to less than 20 μm for near complete pyrite liberation, this year we have invented a new process which we call an electrostatic sieve conveyor. The best performance data can be summarized as follows for Illinois No. 2 coal obtained from the coal bank.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Particle Size</th>
<th>Pyritic Sulfur in Coal (wt%)</th>
<th>Pyritic Sulfur in Cleaned Coal Stream (wt%)</th>
<th>Number of Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELECTROFLUIDIZED BED</td>
<td>100 μm</td>
<td>2.2</td>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>ELECTROSTATIC SIEVE CONVEYOR</td>
<td>40 μm</td>
<td>2.3</td>
<td>0.96</td>
<td>4</td>
</tr>
<tr>
<td>IMPROVED ELECTROSTATIC CONVEYOR</td>
<td>20 μm</td>
<td>2.3</td>
<td>0.68</td>
<td>1</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

Most of Illinois coal cannot be burned directly because its sulfur content is too high to meet present air pollution requirements. Hence we are developing improved dry electrostatic coal cleaning methods to remove inorganic sulfur found in coals. The proposed dry electrostatic methods have a clear advantage over wet techniques when coal is burned in pulverized form. The problems with the wet methods such as froth flotation that have gained a commercial status include the need to dry the coal, the handling of corrosive coal slurries and pollution and disposal of refuse. Electrostatic methods used in the past involved expensive rotor-type machines which involved scraping of solids that stuck to the electrodes.

The diagram below shows an example of this old technology which is being further developed under the sponsorship of the U.S. Department of Energy (Chem. Week, 1981; Chem. Eng. 1984)

OLD ROTOR TYPE ELECTROSTATIC SEPARATOR

During the past three years under the sponsorship of the Department of Energy and Natural Resources of the State of Illinois and the Coal Development Board we have invented several new, energy efficient techniques to continuously remove iron pyrites from Illinois Coal. One invention consists of a fluidized bed with perforated electrodes. Finely ground coal is fed into the fluidized bed and is split into two streams that leave through the perforated electrodes producing a clean coal stream and a pyrite enriched stream.

The electrofluidized bed system was tested with synthetic mixtures of coal and pyrites and was found to work well. See Gidaspaw, et al. "Electrostatic Desulfurization of Coal in Fluidized Beds and Conveyors", in "New Developments in Fluidization and Fluid Particle Systems", AIChE Symposium Series No. 225, Vol. 83, pp 74-85 (1987). The system also works well for coal ground to no less than about 70 μm. For Illinois No. 2 coal obtained from the State Coal Bank (Colchester Coal) the pyritic sulfur content was reduced from 2.2% to 1.0% in 4 stages. Our model for electrofluidization developed as a part of this project shows that improvements can be made. See Shih, et al., "Hydrodynamics of Electrofluidization: Separation of Pyrites from Coal" AIChE Journal, Vol. 33, pp 1322-1333 (1987).

Unfortunately we have shown this year in agreement with the findings of the State Geological Survey that Illinois No. 2 coal and probably other coals
found in the coal bank must be ground much finer than 100 μm for a near complete pyrite removal by any physical methods, wet or dry. This was done by scanning electron microscope tests and by actual physical separation. This led us to use our new methods of separation: electrostatic sieve conveyors.

The figures below show the new electrostatic sieve conveyor and pyritic sulfur in the clean coal stream for Illinois No. 2 coal ground to an average size of 40 microns as a function of a number of passes. To reduce the pyritic sulfur below 0.86% modeling indicates that all pyritic sulfur can be removed in one pass in an improved conveyor.

To improve the performance of the electrostatic conveyor and electrofluidized beds, we made measurements of surface charge of pyrites and coal as a function of humidity and flow rates. These data were presented at the Annual Meeting of the American Chemical Society. See Mukherjee, et al., "Surface Charge of Illinois Coal and Pyrites for Dry Electrostatic Separation" ACS preprints, Division of Fuel Chemistry, pp 395-407 (1987). These data and the mathematical model for the conveyor that we developed this year helped us to improve the conveyor. The figure below shows the improved conveyor.
In this conveyor we are able to reduce the pyritic sulfur of Illinois No. 2 coal from the coal bank from 2.3% pyritic sulfur to 0.68% in one pass. The coal was ground to 20 μm. We obtained 85% separation of liberated pyrites.

These data indicate to us that we can obtain compliance coal by grinding it to below 20 μm. This coal can then be burned directly in pulverized form. The electrostatic sieve conveyor would be simply located between the grinder and the burner.
INTRODUCTION

Dry methods of pyrite removal from coal are known to be more energy efficient than wet methods. Fig. 1 compares the energy losses for two wet processes to our electrostatic dry process using our present sieve conveyor. The first wet process in Fig. 1 is the aggregate two stage froth flotation process being developed by the State of Illinois. For one ton per hour of coal the energy loss is 876 KWH. The energy loss for our proposed process is 220 KWH using an electrostatic sieve conveyor. Using an electrofluidized bed this loss is only 42 KWH.

Furthermore, electrostatic methods used in the past (Inculet, et al 1982; Ralston, 1961; Gidaspow, et al 1986) involved expensive rotor-type machines which involved scraping of solids that stuck to the electrodes. Using an electrostatic sieve concept we have solved both the problems of sticking and the problem of costly rotating machinery used in the past. (Gidaspow, et al 1986).

Our novel concept of removal of pyrites is illustrated in Figure 2. Powdered material is fed into the unit. Since the pyrites carry a charge more negative than coal (Mukherjee, et al 1987), they preferentially move away from the negative electrode creating a pyrite-clear boundary layer. Coal is removed through a perforated sieve-type electrode. The rate of removal of the coal is determined by its electrophoretic mobility as shown in this figure. We have applied this concept to continuous separation in electrofluidized beds and to sieve conveyors.
A. SEPARATION IN CONTINUOUS ELECTROFLUIDIZED BEDS

Our experiments (Gidaspow, et al. 1985; Saxena, 1985) of electrostatic separation of synthetic mixtures of iron pyrites and Illinois No. 6 coal in a batch electrofluidized bed have shown the feasibility of this method of separation. Based on this experience we have constructed and tested a continuous electrofluidized bed which can serve as a rough prototype of a commercially useful electrofluidized bed. Figure 3 shows a sketch of the apparatus. The details are discussed in our annual report to the State of Illinois (Gidaspow, et al., 1985) and the MS thesis by Saxena (1985). Saxena has tested this unit with synthetic mixtures of coal and iron pyrites.

Figure 4 shows the removal of iron pyrites from two Illinois coals which were ground under a nitrogen atmosphere to an average particle size of 100 and 75 microns, as shown. Stage number in Fig. 4 refers to the recycling of the clean coal stream obtained in the previous stage. All the samples were chemically analyzed using an ASTM method for pyritic sulfur determination as done by the State Geological Survey.

From Fig. 4 we see that we can remove about 25% of pyritic sulfur in one stage, with the finer ground coal giving us a better separation. However, the figure also indicates that the pyritic sulfur removal levels out with staging. This is most likely due to the fact that the coal had not been ground to a sufficiently small particle size to liberate the pyrites. Our observation is confirmed by the characterization of pyrites done by the State of Illinois Geological Survey. They report the mean free pyrite diameter in Illinois No. 2 coal to be 3.36 microns.

Figure 5 shows the mass flow rates for the streams in the electrofluidized bed for Illinois No. 2 coal ground to an average particle size of 100 microns. The inlet flow is split approximately equally into a clean coal stream and a
Figure I

A COMPARISON OF ENERGY LOSSES IN WET PROCESSES WITH DRY ELECTROSTATIC PROCESS FOR SEPARATION OF PYRITES IN COAL

Basis: 1 Ton/Hr. of -28 mesh Raw Coal Feed and a separation of 90% for pyrites

BTU Generated: 7753 KWH/TON

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**WET PROCESS-I**

2-STAGE FROTH FLOTATION

ROM COAL

- WASHING
- CRUSHING
- SCREENING (28 mesh)

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**WET PROCESS-II**

HIGH GRADIENT MAGNETIC SEPARATION

ROM COAL

- WASHING
- CRUSHING
- SCREENING (28 mesh)

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**DRY PROCESS**

ELECTROSTATIC SIEVE CONVEYING

ROM COAL

- WASHING
- CRUSHING
- SCREENING (28 mesh)

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**Energy Losses**

<table>
<thead>
<tr>
<th>Wet Process I</th>
<th>Wet Process II</th>
<th>Dry Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 KWH</td>
<td>21 KWH</td>
<td>28 KWH</td>
</tr>
<tr>
<td>WET GRINDING</td>
<td>WET GRINDING</td>
<td>DRY GRINDING</td>
</tr>
<tr>
<td>(80% -400 mesh)</td>
<td>(80% -400 mesh)</td>
<td>(80% -400 mesh)</td>
</tr>
<tr>
<td>Surfactants</td>
<td>Clean Coal Slurry</td>
<td>Clean Coal Slurry</td>
</tr>
<tr>
<td>Clean Coal (20% Coal)</td>
<td>20% Coal</td>
<td>20% Coal</td>
</tr>
<tr>
<td>Cake (25% moisture)</td>
<td>Cake (25% moisture)</td>
<td>Cake (25% moisture)</td>
</tr>
<tr>
<td>THERMAL DRYING</td>
<td>THERMAL DRYING</td>
<td>THERMAL DRYING</td>
</tr>
<tr>
<td>Clean Coal (10% moisture)</td>
<td>Clean Coal (10% moisture)</td>
<td>Clean Coal (10% moisture)</td>
</tr>
<tr>
<td>528 KWH</td>
<td>528 KWH</td>
<td>100 KWH</td>
</tr>
<tr>
<td>Total Energy Loss= 876.0 KWH</td>
<td>Total Energy Losses= 705 KWH</td>
<td>Total Energy Losses= 220 KWH</td>
</tr>
</tbody>
</table>
To obtain a layer that is free of pyrites,

\[ V_{\text{pyrite}} \geq V_{\text{coal}} \]

through sieve

Where \( V \) is the velocity.

\[ V = EM \cdot E \]

Where EM is the electrostatic mobility and \( E \) is the electric field strength, volts/cm.

Fig. 2 Electrostatic Sieve Concept for Removal of Pyrites from Coal.

Fig. 3. Electro-fluidized bed in IIT Laboratory with Perforated Electrodes.

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**Fig. 4.** Removal of Pyritic Sulfur from Illinois Coals in the Electro-fluidized Bed.

**Fig. 5.** Flow Rates of Inlet, Clean Coal and Pyrite Enriched Stream in the Electro-fluidized Bed Corresponding to Data in Fig. 4.
pyrite enriched stream.

Figure 6 shows the potential of concentrating the iron pyrites obtained from the pyrite streams and thus potential coal recovery. For the Illinois No. 2 coal ground to 60 microns the flow rates for the pyrite stream were unfavorable, made intentionally to produce cleaner coal. Hence the concentration is poor. For the Illinois No. 6 coal the pyrite concentration is exceptionally high due to the use of only a large particle size fraction equal to approximately 150 microns in diameter.

Processing of coal ground to finer than 100 microns presents flow problems which we are solving.

B. SEPARATION OF PYRITES FROM COAL IN AN ELECTROSTATIC SIEVE CONVEYOR.

In view of the limitations of the electrofluidized bed for processing coals much below 100 microns and the perceived need to grind Illinois coals below that size for near complete pyrite liberation, we have invented a new separation device. We call it an electrostatic sieve conveyor. It is based on the electrostatic sieve concept we had described in our 1986 Annual Report to the State of Illinois. A perforated electrode allows coal to pass through it, while blocking the passage of pyrites. See Fig. 2.

Pyrites were separated from Illinois No. 2 coal using our new Electrostatic Sieve Conveyor. Figure 7 shows the schematic diagram of the apparatus. Figure 8 shows the details of the conveyor. The powdered coal stream containing pyrites is split into two portions on application of an electric field: a clean coal stream and a pyrite-enriched stream. Separation experiments were conducted in dense phase, as well as in the dilute phase, with coal ground 80% to less than 40 microns.

In dense phase operation, the screw feeder, shown in Figure 7 was not used. Instead a hopper containing coal under pressure was used as the feeding system.
system.

Table I shows the results of the separation. It is observed that the pyritic sulfur content can be reduced from an initial value of 2.16% to about 1.7% with a 10,000 volt applied electric field. A major drawback with the dense phase system is that the flow of solids cannot be easily controlled. To avoid this problem, a screw feeder with a variable drive motor was used as the feeding system, and the solids were made to flow in dilute phase. The results of the experiments are shown in Table I. We see that without an electric field the removal of pyrites was negligible. With an increasing electric field better separation is possible. With a 18,000 volt electric field, the pyritic sulfur in clean coal can be brought down to about 1.4% in one stage.

Figure 9 shows the removal of iron pyrites ground to an average size of 40 microns with recycling. The pyritic sulfur was reduced to 0.86% after four stages with an equal split of streams. The figure also indicates that further reduction is not possible. To obtain greater pyrite removal, it is necessary to grind the coal to a finer size. Such work is in progress.

### TABLE I. SEPARATION OF PYRITES USING AN ELECTROSTATIC SIEVE CONVEYOR

**Feed:**

Illinois #2 Coal from the Coal Sample Bank  
Initial Pyritic Sulfur = 2.16% (4.05% FeS₂)  
Particle size less than 53 μm (80% < 40 μm)

**RESULTS**

a. **Dense Phase Flow**

<table>
<thead>
<tr>
<th>Applied Voltage</th>
<th>Conc. of Pyritic Sulfur 1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000 V</td>
<td>1.68 (3.15% FeS₂)</td>
</tr>
<tr>
<td>5,000 V</td>
<td>1.81 (3.39% FeS₂)</td>
</tr>
</tbody>
</table>

b. **Dilute Phase Flow**

<table>
<thead>
<tr>
<th>Applied Voltage</th>
<th>Conc. of Pyritic Sulfur 1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 V</td>
<td>2.18 (4.08% FeS₂)</td>
</tr>
<tr>
<td>5,000 V</td>
<td>1.81 (3.39% FeS₂)</td>
</tr>
<tr>
<td>10,000 V</td>
<td>1.54 (2.85% FeS₂)</td>
</tr>
<tr>
<td>18,000 V</td>
<td>1.42 (2.68% FeS₂)</td>
</tr>
</tbody>
</table>
Fig. 6. Concentration of Pyrites Illustrating Potential Coal Recovery.

Fig. 7. Electrostatic Sieve Conveyor System

Fig. 8. Electrostatic Sieve Conveyor

Fig. 9. Removal of Pyrites in an Electrostatic Sieve Conveyor with Stream Recycling for Illinois No. 2 Coal Ground to 40 \( \mu \)m.
A HYDRODYNAMIC MODEL

Hydrodynamic models of fluidization use the principles of conservation of mass and momentum for each phase, Gidaspow (1986) has given a detailed review of the hydrodynamic modeling of fluidization. The model developed here for electrofluidization is essentially an extension of the K-FIX algorithm by Rivard et al. (1977). The K-FIX computer code is written in a modular form and has been demonstrated to be adaptable to a variety of multi-phase flow problems as described by Ettehadieh (1982) and Syamlal (1985). Syamlal (1985) and Gidaspow, et al. (1986) present a manual for an extension of the K-FIX algorithm to three phases. Table II summarizes the equations used in the model, with symbols defined in Table III.

Surface Charge of Particles

To model the electrostatic sieve conveyor, we need to know the surface charges of particles. The electric force acting on a particle in an electrostatic field is the product of its charge and the strength of the electric field applied, i.e. \( q_k E \). Inculet (1982) have indicated that the charging of the particles in a conveyor may take place by tribo-electrification.

A pneumatic conveyor was designed and constructed to conduct a direct measurement of such a charge. The average surface charge per particle was measured by inserting a metallic ball probe through the sides of an electrostatic pneumatic conveyor. The probe which is inserted in the stream of charged particles will pick up a current that is proportional to the charge of the particles. Details of the experimental measurements were reported by Mukherjee (1987). The average surface charges of coal and pyrite particles obtained at various dew point temperatures and mass flow rates were also reported by Mukherjee (1987). Both coal and pyrite particles carry negative charges. The average size of the particles used in the experiments was 212 \( \mu \)m. Experimental work is continuing. Although such surface charges of particles
TABLE II GOVERNING EQUATIONS

Continuity Equations
\[
\frac{3}{8} \varepsilon_k c_k + \nabla \cdot (\rho_k c_k \vec{v}_k) = 0
\]  \hspace{1cm} (2)

Momentum Equations
\[
\frac{3}{8} \varepsilon_k c_k \vec{v}_k + \nabla \cdot (\rho_k c_k \vec{v}_k \vec{v}_k) = -\varepsilon_k \vec{v}^2 \rho_1 + \rho_k c_k \vec{v}_k + G_k \nabla \varepsilon_k
\]  \hspace{1cm} (3)

where,
\[
\sum_{k=1}^{N} \varepsilon_k = 1
\]  \hspace{1cm} (4)

Equation of State
\[
\rho_1 = \frac{\rho}{RT}, \quad \rho_k = \rho_{sk} \quad \text{for } k \geq 2
\]  \hspace{1cm} (5)

Gas-Particle Friction
\[
K_{k1} = C_{Dk} = \frac{150(1 - \varepsilon_1) c_k \mu_1}{\varepsilon_1 (d_k \varepsilon_k)^2} + \frac{1.75 \rho_1 |\vec{v}_1 - \vec{v}_k| c_k}{(d_k \varepsilon_k)^2}
\]  \hspace{1cm} (6)

where,
\[
f(\varepsilon_1) = \varepsilon_1^{-2.55}
\]  \hspace{1cm} (7)

\[
C_{Dk} = \frac{24}{Re_k} \left(1 + 0.15 Re_k^{0.687} \right), \quad \text{for } Re_k < 1000
\] \hspace{1cm} (8)

\[
= 0.44, \quad \text{for } Re_k \geq 1000
\]

and
\[
Re_k = \frac{d_k |\vec{v}_1 - \vec{v}_k| \rho_1 \varepsilon_1}{\mu_1}
\]  \hspace{1cm} (9)

Particle Particle Interaction
\[
K_{kl} = \frac{3}{2} \alpha(1 + e) \frac{c_k c_l d_k d_l (d_k + d_l)^2}{\sigma_k d_k d_k + \sigma_l d_l d_l} |\vec{v}_k - \vec{v}_l|
\]  \hspace{1cm} (10)

Solids Stress
\[
G_k = \begin{cases} 0 & \text{for } k = 1 \\ e_k G(e_k) & \text{for } k = 2, \ldots, N \end{cases}
\]  \hspace{1cm} (11)

where, \[G(e_k) = -10^{-8.76 e_k} + 7.8\]
TABLE - III. NOMENCLATURE

\begin{align*}
\text{a}_b & : \text{Radius of Bubbles} \\
\text{a}_p & : \text{Radius of Particles} \\
C_{Dk} & : \text{Gas Particulate Phase } k \text{ Drag Coefficient} \\
D_b & : \text{Diameter of Bubble} \\
D_{b0} & : \text{Initial Diameter of Bubble} \\
d_k & : \text{Characteristic Diameter of Particulate Phase } k \\
d_p & : \text{Diameter of Particles} \\
e & : \text{Coefficient of Restitution} \\
E & : \text{Externally Applied Electric Field Strength} \\
EM & : \text{Electrophoretic Mobility} \\
F_e & : \text{Electrical Force Acting on Particles} \\
F_g & : \text{Gravitational Force Acting on Particles} \\
f & : \text{Function Defined by Equation (7)} \\
G & : \text{Solid Stress Modulus} \\
g & : \text{Gravitational Acceleration} \\
h & : \text{Distance Above Distributor} \\
K_{kl} & : \text{Generalized Drag Coefficient Between Phases } k \text{ and } l \\
L & : \text{Height of Fluidized Bed} \\
L_p & : \text{Jet Penetration Depth} \\
N & : \text{Total number of Phases} \\
P & : \text{System Pressure} \\
q & : \text{Surface Charge of Particles per Unit Volume of Mixture} \\
Re & : \text{Reynolds Number for Particular Phases} \\
T & : \text{System Temperature} \\
t & : \text{Time} \\
U & : \text{Horizontal Component of Velocities} \\
U_b & : \text{Bubble Rising Velocity} \\
U_{mf} & : \text{Minimum Fluidization Velocity} \\
v & : \text{Velocity Vector of Phases} \\
V & : \text{Vertical Component of Velocities} \\
V_{s,\text{critical}} & : \text{Critical Flow Velocity} \\
W & : \text{Width of Fluidized Bed} \\
\alpha & : \text{Non-head-on Collision Factor Defined by Equation (10)} \\
\delta_r, \delta_y & : \text{Mesh Sizes} \\
\epsilon & : \text{Volume Fraction} \\
\mu & : \text{Viscosity} \\
\phi & : \text{Characteristic Shape Factor of Solids Phase} \\
p & : \text{Density} \\
\text{Subscripts} & : \text{Phase } k \\
k & : \text{Phase } k \\
I & : \text{Fluid Phase} \\
s & : \text{Particulate Phase}
\end{align*}
may be a function of particle velocity, a constant surface charge of particles was used in the calculations. The values used were:

\[ q_{\text{pyrite}} = 5 \times 10^{-12} \text{ Coulombs/particle} \]
\[ q_{\text{coal}} = 3 \times 10^{-13} \text{ Coulombs/particle} \]

RESULTS OF SIMULATION

The computer model was applied to separation of pyrites from coal in the electrostatic sieve conveyor pictured in Figure 10. This geometry is not identical to the experiment but serves as an approximation due to difficulties of modeling the holes in the sieve in the experiment. Typical computed coal and pyrite concentrations are shown by means of a standard dot plot in Figure 11. With an applied field of 1800 volts/cm we see that we have a nearly clear pyrite free layer near the top electrode. We also see that a better performance can be obtained. The outlet computed pyrite concentrations in the coal stream were compared to the experimental values measured in the same conveyor as shown in Figure 12. We see that the predictions are in a reasonable agreement with the measured values considering that not all of the pyrites were liberated in the experiment. The model therefore gives a somewhat better performance. When the width of the conveyor was increased to 20 cm and the voltage to 60,000 volts the pyrite concentration was reduced to near zero in the clean coal stream. This shows that an improved electrostatic conveyor can reduce the pyrite concentration to near zero once the pyrites have been liberated by grinding or by other methods.
ELECTRIC FIELD STRENGTH = 1000 VOLTS/CM

SOLID FLOW RATE = 1.18 kg/min

\[ \text{\textit{v_{wood}} = 200\text{cm/sec}} \]
\[ \text{\textit{v_{coal}} = 200\text{cm/sec}} \]
\[ \text{\textit{v_{pyrites}} = 200\text{cm/sec}} \]

Figure 10. Geometry and Inlet Conditions for an Electrostatic Conveyor Used in Computer Simulations.

COAL CONCENTRATION

PYRITES CONCENTRATION

Figure 11. Computed Coal and Pyrite Concentrations at a Steady State with an 18,000 volt Electric Field.

Figure 12. A Comparison of Computed (Dashed Curve) Outlet Pyrite Concentrations to Experimentally Determined FeS\textsubscript{2} in the Sieve Conveyor.
PYRITE CHARACTERIZATION IN ILLINOIS #2 COAL BY SEM

To determine the extent of grinding and the possibility of separating mineral inclusions, mainly iron pyrites, from Illinois #2 coal, the distribution of mineral inclusions in coal matrix and its composition were studied using a scanning electron microscope (SEM) at IIT Research Institute. An Illinois #2 preparation plant sample was obtained from Illinois State Geological survey and used in this study. Representative specimens of particle sizes of 150μm, 100 μm and 20 μm were made by grinding the coal under nitrogen in a micropulverizer and in a jet mill and suitably coating them with gold or graphite. Figure 13 shows a typical electron micrograph of 20 μm sample. For each specimen, 20 particles were randomly taken and analyzed by X-ray diffraction trace. Figure 14 is an X-ray diffraction trace for one of the 20 μm particles.

Based on the above observations, a plot of percent pyrite liberation versus particle size was made, as shown in Figure 15. This graph indicates that approximately 90% pyrites are liberated at an average particle size of 20 μm. However, the complete liberation of pyrite requires grinding coal below 3 μm particle size. This observation was confirmed by a study done at Illinois State Geological Survey on similar samples. They report the mean diameter of free pyrite as 3.36 μm. Also, in a study done by Kneller et al. (1985) for Ohio and Pittsburgh. Coals, pyrite grain diameters were reported between 4-8 μm.

Ultrafine dry grinding of coal to less than 20 μm particle size is an energy intensive process. Figure 16 shows the theoretical energy required for grinding the coal from a feed size of 1168 μm (28 MESH) to a desired particle size. We see that the energy required to grind the coal to 20 μm size is around 20 KWH/ton and 126 KWH/ton for 1 μm in size. However, this number is still very low compared to the energy consumption in the commercially available Froth Flotation process as shown in Figure 1.
Figure 13. Scanning Electron Micrograph of a 20μm Illinois #2 Coal Particle

Figure 14. X-ray Diffraction Trace of a 20μm Coal Particle.

Figure 15. Percent Pyrite Liberation as a Function of Coal Particle Size (Number Distribution).

Figure 16. Theoretical Energy Required to Grind the Coal from 28 Mesh to Given Product Size.
SEPARATION OF PYRITES FROM ILLINOIS COAL IN THE IMPROVED CONVEYOR

Pyrites were separated from Illinois #2 Coal using an Electrostatic Sieve Conveyor shown in Figure 17. This conveyor is a modification of the one described in the previous section, as shown in Figure 8. In the previous conveyor, both the efficiency of pyrite removal and coal recovery were poor due to the uncontrolled mixing of particles. Therefore, we computed the flow of coal and pyrite particles in the conveyor using our hydrodynamic model described in previous sections. We arrived at the design shown in Figure 17. The computer simulations show that both pyrite removal and coal recoveries are good for this geometry.

To run the experiments, Illinois #2 Coal was first crushed using a Bantam Micropulverizer to an average particle size of 53 μm. The coal was further ground to an average size of 20 μm in a Micron Master jet mill. The coal was then dried to remove the surface moisture.

The finely ground coal was fed into a hopper and conveyed to the separator by means of a screw feeder. Several runs were made at various gas velocities at a constant coal mass flow rate.

Unlike in the previous separator, a tribocharger was required for this unit since there was very little rubbing of the particles, otherwise. The tribocharger used was an aluminium honeycomb distributor typically used in air conditioning equipment. The tribocharger was placed at the entrance of the conveyor to charge the coal and pyrite particles before entering into the conveyor.

A voltage of 1800 volt/cm was used in the experiments. Since pyrites carry a more negative charge than coal, the concentration of pyrites was more at the positive electrode where the pyrite enriched stream was withdrawn from the bottom while the clean coal was carried towards the farther end of the conveyor. Table IV shows the experimental data.
Figure 18 shows the results of pyrite removal at various gas flow rates. Best separation of pyrites was possible at a gas velocity of 228 cm/sec, where the level of pyritic sulfur was reduced from 2.3% to 0.68%. This corresponds to a removal of about 72% of the total pyritic sulfur or about 85% of the liberated pyritic sulfur in one stage. Therefore, it should be possible to remove more pyritic sulfur if more pyrites are liberated. This would require grinding the particles to a size between 5-10 μm. Such work is in progress.

Figure 19 shows the comparison of experiments to our hydrodynamic model. Good agreement between experimental and computed results exists. Therefore, we are able to use our model to further improve the separator design for better pyritic sulfur removal and coal recoveries.

TABLE IV

SEPARATION OF PYRITES IN AN IMPROVED CONVEYOR

Applied Voltage = 1800 V/cm
Average Initial Pyritic Sulfur = 2.3% (wt.)
Average Particle Size = 20 μm

(a) Without Tribocharger

<table>
<thead>
<tr>
<th>Run #</th>
<th>Gas Velocity (cm/sec)</th>
<th>% Pyritic Sulfur in Clean Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228.4</td>
<td>1.60</td>
</tr>
<tr>
<td>2</td>
<td>355.0</td>
<td>1.84</td>
</tr>
<tr>
<td>3</td>
<td>440.0</td>
<td>1.96</td>
</tr>
</tbody>
</table>

(b) With Tribocharger

<table>
<thead>
<tr>
<th>Run #</th>
<th>Gas Velocity (cm/sec)</th>
<th>% Pyritic Sulfur in Clean Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228.4</td>
<td>0.68</td>
</tr>
<tr>
<td>2</td>
<td>284.0</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>355.0</td>
<td>1.02</td>
</tr>
<tr>
<td>4</td>
<td>440.0</td>
<td>1.40</td>
</tr>
</tbody>
</table>
Figure 17. IMPROVED ELECTROSTATIC SIEVE CONVEYOR

FIELD
1/2 WALL
THICKNESS TYP.

PYRITE
STREAM

CLEAN
COAL

1/2

3 HOLES

100 cm

30

20

10

Figure 18. Removal of Pyrites in an Improved Electrostatic Sieve Conveyor.

ILLINOIS #2 COAL

□ WITH TRIBOCHEMICAL
• WITHOUT TRIBOCHEMICAL

APPLIED VOLTAGE = 1800 V/cm
AVG. PARTICLE SIZE = 20 μm
AVG. INITIAL PYRITIC SULFUR = 2.3 %

PERCENTAGE PYRITE REMOVAL

GAS VELOCITY (cm/sec)

200 300 400 500

20 30 40 50 60 70 80 90 100

Figure 19. A Comparison of Computed Pyrite Removal to Experimental Data in an Improved Electrostatic Sieve Conveyor.
REFERENCES


