Coal spirals are widely used in coal preparation plants in Illinois and around the world to clean fine coal, typically in the 1 x 0.15 mm size range. Despite their popularity and the trend toward increased automation in modern coal preparation plants, adjustments to the critical process variable for coal spirals, i.e., product splitter position, continue to be done manually. Since spiral feed in a plant tends to fluctuate on a regular basis, suitable manual adjustment of splitter position in tens or hundreds of spirals operating in a plant is nearly impossible. As a result, the clean coal yield from a spiral and also the overall plant suffers on a regular basis.

The main goal of this project was to develop a suitable sensor and control system to adjust the product splitter position of a full-scale spiral. One of the basic properties of coal slurry was thoroughly investigated for its on-line measurability and for its correlation with the constituent solid density of the slurry. After experimenting with electrical capacitance- and conductivity- (i.e., reciprocal of resistivity) based sensing techniques, a conductive-based tube sensor was selected for measuring solids density of particles in the spiral trough. Two sensors were used to establish a density gradient in the critical region across the spiral trough at the discharge end. Based on this continuously monitored density gradient, a PIC24 microcontroller was programmed to send a signal to a DC gear motor that would move the splitter arm when sufficient variation in conductivity was detected. Currently, a cycle time of 5 minutes is used for the spiral control system; however, in a commercial application, the cycle time could be lengthened to 30 or 60 minutes. The automation system has been validated by examining the performance of a full-scale spiral while deliberately changing factors like feed solid content, feed washability characteristics, and feed slurry ionic concentration. With compound spirals programmed to achieve a specific gravity of separation at 1.65, actual $D_{50}$ values achieved for two separate tests were 1.64 and 1.73. The close proximity of target and actual $D_{50}$ values is indicative of the effectiveness of the developed system. The next step in near-term commercialization of this proprietary spiral control system will be a longer term (several months) in-plant demonstration.

Pages 8-28 contain proprietary information.
EXECUTIVE SUMMARY

Coal spirals typically clean 70% of the feed to the fine coal circuit of a preparation plant, or 6 to 8% of the entire run-of-mine coal in most cases. Spiral concentrators are widely used in coal preparation plants in Illinois and elsewhere due to their ease of operation, low cost, and ability to achieve high clean coal yield. However, unlike most other density-based coal cleaning systems, spiral separators have no means of being controlled automatically from a plant control room through a PLC. In fact, the spiral circuit is the only section of a modern day preparation plant, which has yet to be automated.

Fluctuating feed conditions commonly encountered in a plant may include changes in feed quality, i.e., coal washability characteristics, or changes in feed or quantity, i.e., mass flow of solids reporting to the spiral circuit. These changes affect spiral cleaning performance, which is not accounted for if the spiral splitter is maintained in the same position. Adjustment of the splitter position is required to maintain a constant density cut-point through these fluctuations that are due to changes in the mine workings. Past studies (Abbott, 1982; Luttrell et al., 2003) indicate that it is essential to maintain the same density cut point in each spiral in a spiral bank to achieve the maximum yield from a spiral circuit. In addition, it is well known that preparation plants operating with multiple, parallel cleaning circuits for different size fractions of coal can provide the best possible plant yield for a given product quality only if the incremental product quality achieved in each cleaning circuit is maintained at the same level. In other words, the density cut point must be held constant throughout the plant.

This study together with a previous ICCI-funded project (Mohanty and Mahajan, 2007) led to the successful development of a proprietary automation system to adjust the splitter position of a full-scale spiral in a fluctuating feed environment. The spiral automation system operates on the principle that the electrical conductivity of solid particles is different for different types of solid materials. It is well known that the specific gravity of coal is linearly correlated to its ash content; the higher the specific gravity, the higher the ash content. It is also well established that coal ash content is a function of mineral matter content. Considering the fact that electrical conductivity of most mineral matter is much higher than that of carbonaceous matter present in coal, a direct correlation between electrical conductivity and specific gravity of coal was established, as illustrated in Figure 1. These conductivity measurements were made on the solid sample collected from different sections across the trough of a full-scale spiral operating at SIU’s pilot-scale research facility.
SIU’s automation system includes two conductivity-based sensors, a PIC microcontroller, two tabular solenoids, and a newly designed splitter box with a vertical splitter controlled by a DC gear motor that moves forward (inward) or backward (outward) to maintain a constant specific gravity cut point. The sensor consists of two stainless steel rings connected to two Plexiglas tubes. The two sensors are used to establish the conductivity gradient and thus, the density gradient in the critical region (about 7 inch long) across the spiral trough at the discharge end. A PIC24 microcontroller then sends a signal to the DC gear motor to turn clockwise or counter-clockwise or stay at the same position based on the difference between the conductivity/density measurement of the present cycle and that of the previous cycle. Currently, a cycle time of 5 minutes is used for the spiral control system; however, in a commercial application, the cycle time could be lengthened to 30 or 60 minutes. The automation system has been validated by examining the performance of a full-scale spiral while deliberately changing factors like feed solid content, feed washability characteristics, and feed slurry ionic concentration. With compound spirals programmed to achieve a specific gravity of separation at 1.65, actual $D_{50}$ values achieved for two separate tests were 1.64 and 1.73, respectively. The close proximity of target and actual $D_{50}$ values is indicative of the effectiveness of the newly developed spiral control system.

An in-plant project is proposed for the near future to demonstrate the suitability of the automation system by operating it on a continuous basis, for weeks and months in a real plant environment. A much larger splitter-box will be designed and fabricated to fit on the discharge end of a set of triple-start spirals (three spiral units on the same footprint). The electronic circuitry may require adjustment for its operation in the plant environment. The field environment will experience larger temperature variations than

Figure 1: Correlation of electrical conductivity with specific gravity for carbonaceous and mineral matter present in coal.
encountered during pilot-scale test work. Temperature affects both conductivity of the sample being measured and circuit performance (offset of measurement results). This will be addressed by adding electronic circuitry to monitor slurry temperature at different time periods and adjust for its effect. Another concern in the field environment may be the impact of environmental electromagnetic interference (EMI). The field environment will be noisier than the lab setting. It is possible that noise caused by EMI could hinder the collection of meaningful data from sensors. Depending on the actual environment, additional filtering may have to be added to the circuit. The DC motor will be larger with more power to actuate and move the splitter, which will be common to all three spiral starts.

After establishing a smooth operational track record for the automation system, it will be allowed to operate continuously for a period of up to three months. Feed, product, and tailings samples from the automated spiral and adjacent conventional spirals operating in the plant will be collected on a daily basis to examine the true benefit of having a smart spiral (spiral + automation system) over a conventional spiral. This benefit will be translated to a dollar value, which should quickly attract the attention of prospective end users leading to near-term commercialization of the technology. In preparation for this, SIU’s Technology Transfer Group is initiating the patent application process to protect the spiral automation technology developed as a part of this ICCI-funded project.
OBJECTIVES

The overall goal of this project was to develop a low-cost, on-line control system for coal spirals that automatically adjusts their splitter position with any significant change in feed characteristics to maintain the same level of cleaning performance. Specific project objectives were:

- Development of a suitable sensor for a full-scale spiral.
- Demonstration of the functionality of the automation system by testing it with a full-scale spiral.
- Economic analysis to justify the viability of the spiral automation system.

INTRODUCTION AND BACKGROUND

Spiral concentrators were first utilized within the mineral industry for the treatment of chrome-bearing sands in the 1940s. Test work conducted in the early 1950s demonstrated that reasonable separation between low-ash coal and high-ash mineral matter could be achieved using Humphrey’s coal spirals. Now spiral concentrators are being widely used in coal preparation plants world-wide to treat material commonly in the particle size range of 1 mm x 150 micron, which is too coarse to be effectively cleaned by froth flotation and too fine for efficient cleaning in heavy medium cyclones. Furthermore, recent studies (Zhang et al., 2008; Honaker et al., 2007) have reported that high efficiency separation was obtained from coal spirals for fine coal cleaning up to a bottom size of 45 micron. The major factors which result in the popularity of coal spiral concentrators are their advantageous characteristics, such as high recovery, low capital and operating costs, no chemical reagent or dense medium requirement, and the ease of operation and maintenance.

The cleaning performance of the spiral concentrator is achieved as a result of two types of material flows: a primary downward flow and a secondary transverse flow across the spiral profile. It is the transverse flow that creates a density gradient across the spiral trough, as illustrated in Figure 2 (rock has higher density than coal), whereas the primary flow carries the density gradient down to the discharge end. Typically, two splitters are used at the discharge end to produce three product streams, namely clean coal, middlings, and tailings. It is also a common practice to merge the middling stream to either product or tailing stream based on the product quality specification that is satisfied by the plant. Product splitters are typically so placed that the entire upper section as well as the upper portion of the lower section report to the clean coal launder. Understandably, the ideal location for the product splitter position is not fixed. It is a function of solids loading (the amount of solids on the spiral profile), volumetric flow (the amount of total slurry on the profile), and washability characteristics (the type of coal being treated) at a given point in time. Since all three conditions fluctuate in a plant environment, the ideal location for the splitter position also shifts. However, it is rare to see the splitter position of operating coal spirals changed once fixed at their initial location. This results in a significant loss of recoverable clean coal.
To verify the possible loss of clean coal due to the unaltered position of the splitter in the fluctuating feed environment, two tests (Tests 1 and 4) were conducted where the solid content varied from 34% for Test 1 to 20% for Test 4, while maintaining volumetric flow rate and feed coal quality at the same levels. Product samples were collected from a test spiral having six discharge ports (F to A), as shown in the schematic diagram of Figure 3. Test samples were analyzed to generate yield-ash relationships as a function of splitter position (from 1 to 5 with 1 being the position between E and F, 2 between D and
E, and so on). As shown in Figure 4, if the splitter position was maintained at position 4, yield and product ash will decrease from 73.2% and 13.9%, respectively in Test 1 to 68.5% and 11.2%, respectively in Test 4. The 4.7% reduction in spiral yield could be almost completely avoided by adjusting the splitter position to 3 from 4 with the decrease in the feed solid content from Test 1 to Test 4, as illustrated in Figure 4.

![Figure 4: Effect of solids loading on coal spiral product yield and product ash.](image)

The other reason for having a control system to automatically adjust the splitter position in a coal spiral is directly related to the overall performance of the plant. It is well known that incremental ash for individual coal cleaning units has to be maintained at the same level in order to maximize the overall plant yield for a given product quality. Unfortunately, the coal spiral circuit is the only section of a modern day coal preparation plant that is not automated; in other words, it cannot provide the same incremental ash if feed condition changes. It is, therefore, imperative to develop an automatic control system for plant spirals to adjust the splitter position to provide the same incremental ash content by maintaining the same density cut point.

The literature on spiral automation systems is very limited. Two different control strategies have been attempted to automatically control the splitter position of a spiral concentrator. Vermaak et al. (2008) developed an optical technique for mineral sands application to detect the mineral-gangue interface, which is a function of feed characteristics. They investigated the effectiveness of controlling the product recovery and grade by adjusting feed parameters. However, such an optical system is not suitable for the coal cleaning spiral application since a clean coal-gangue interface is almost impossible to detect optically due to the presence of slimes in the coal spiral feed slurry.

Mohanty and Mahajan (2007), through a previous ICCI grant, attempted to develop an automation system for a coal spiral. The outcome of this project was the development of a low-cost control system and testing of several slurry density sensing methods. However, strain gauge-based sensors tested in this project are not suitable for full-scale
Task 6: Economic Analysis

To determine the cost of retrofitting a triple-start coal spiral with the automated splitter control system, individual hardware components for the developed system were listed in Table 7 and a price obtained for each based on 2011 costs.

Table 7: Components costs for retrofitting a triple-start coal spiral with an automated control system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors</td>
<td>$2.00</td>
</tr>
<tr>
<td>Operational amplifier</td>
<td>$8.00</td>
</tr>
<tr>
<td>Switches, LEDs, wires</td>
<td>$10.00</td>
</tr>
<tr>
<td>Resistors, capacitors</td>
<td>$2.00</td>
</tr>
<tr>
<td>PIC microcontroller</td>
<td>$8.00</td>
</tr>
<tr>
<td>Mosfet and optoisolator</td>
<td>$10.00</td>
</tr>
<tr>
<td>Power supplies</td>
<td>$150.00</td>
</tr>
<tr>
<td>Seals, bolts, nuts</td>
<td>$20.00</td>
</tr>
<tr>
<td>Splitter box</td>
<td>$20.00</td>
</tr>
<tr>
<td>Solenoids</td>
<td>$50.00</td>
</tr>
<tr>
<td>DC motor</td>
<td>$70.00</td>
</tr>
<tr>
<td>Printed circuit board (PCB)*</td>
<td>$20.00</td>
</tr>
<tr>
<td>Pipes and fitting*</td>
<td>$30.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$400.00</strong></td>
</tr>
</tbody>
</table>

*Required for on-site demonstration

CONCLUSIONS AND RECOMMENDATIONS

An automation and control system for a full-scale coal spiral was successfully developed to adjust its splitter position in a fluctuating feed environment and maintain the same specific gravity of separation. The control system consists of two tube sensors, a PIC microcontroller, and a vertical splitter on a rack operated by a DC gear motor. The two conductivity-based sensors monitor material conductivity across the critical separation zone of the coal spiral trough at the discharge end. The PIC microcontroller correlates the conductivity gradient of the solid pack to the specific gravity gradient of solid particles in the feed and determines the exact location of the vertical splitter to maintain in real time the same density cut point for varying feed conditions. The current setup monitors the density gradient for roughly 100 seconds in each five-minute period. If the splitter position needs to be adjusted based on changes in the density gradient established by measured data from the last cycle, the microcontroller signals the DC gear motor to rotate clock-wise or counter-clock-wise until the vertical splitter reaches the appropriate location that has been predetermined to maintain the density cut point. The automation system is estimated to cost $400 per triple-start coal spiral.
Several series of tests were conducted at SIU’s pilot-scale research facility by retrofitting a full-scale compound spiral with the developed spiral control system. The fluctuating feed environment commonly observed in a plant environment was simulated by systematically varying feed conditions from one test series to the next. Key findings obtained from validation tests are listed below:

1. When the microcontroller of the automation system was programmed to achieve a specific gravity cut at 1.65, effective specific gravities of separation obtained in two separate tests were 1.64 and 1.73. The close proximity of target separation density and achieved values is certainly indicative of the effectiveness of the new coal spiral automated control system developed during this study.

2. Standardized performance data, i.e., ash rejection and combustible recovery, remained nearly constant with changes in feed solid content and ionic concentration due to automatic adjustment of the splitter position; however, when feed ash content increased significantly, there was a justifiable downward shift in spiral performance data along the feed washability curve.

For the near-term commercialization of the spiral automation system, the following steps are recommended:

1. An in-plant study is required to demonstrate the efficacy of the system over a long period of time under actual field condition. The field environment will experience larger temperature variations than encountered during the pilot-scale test work completed during this project. Temperature affects both conductivity of the sample being measured and circuit performance (offset of measurement results).

2. Another concern in the field environment may be the impact of environmental electromagnetic interference (EMI). The field environment will be noisier than the lab setting. It is possible that noise caused by EMI inhibits the acquisition of meaningful data from the sensors. Depending on the actual environment, additional filtering may have to be added to the circuit.

3. Since triple start spirals are commonly used in the field to minimize floor space requirements for coal spirals, a much larger splitter box needs to be designed and fabricated so that a single vertical splitter can divide product and tailings streams discharging from individual spiral starts.

4. The automation system should be allowed to operate continuously for a period of at least a few months. Feed, product, and tailings samples from the automated spiral and adjacent conventional spirals operating in the same plant should be collected on a daily basis to determine the true benefit of a “smart spiral” (conventional spiral + automation system) over a conventional spiral.
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REFERENCES


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