An Advanced Control System for Fine Coal Flotation

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Ninth Quarter
(April 1, 1998 - June 31, 1998)

AN ADVANCED CONTROL SYSTEM FOR FINE COAL FLOTATION

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ABSTRACT

A model-based flotation control scheme is being implemented to achieve optimal performance in the handling and treatment of fine coal. The control scheme monitors flotation performance through on-line analysis of ash content. Then, based on the economic and metallurgical performance of the circuit, variables such as collector dosage, frother dosage, and pulp level are adjusted using model-based control algorithms to compensate for feed variations and other process disturbances. Recent developments in sensor technology are being applied for on-line determination of slurry ash content.

During the ninth quarter of this project, Task 3 (Model Building and Computer Simulation) and Task 4 (Sensor Testing) were nearly completed, and Task 6 (Equipment Procurement and Installation) was initiated. Previously, data collected from the plant sampling campaign (Task 2) were used to construct a population balance model to describe the steady-state and dynamic behavior of the flotation circuit. The details of this model were presented in the Eighth Quarterly Technical Progress Report.

During the past quarter, a flotation circuit simulator was designed and used to evaluate control strategies. As a result of this work, a model-based control strategy has been conceived which will allow manipulated variables to be adjusted in response to disturbances to achieve a target incremental ash value in the last cell of the bank. This will, in effect, maximize yield at an acceptable product quality.

During this same period, a video-based ash analyzer was installed on the flotation tailings stream at the Moss No. 3 preparation plant. A preliminary calibration curve was established, and data are continuing to be collected in order to improve the calibration of the analyzer.

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EXECUTIVE SUMMARY

Over the past thirty years, process control has spread from the chemical industry into the fields of mineral and coal processing. Today, process control computers, combined with improved instrumentation, are capable of effective control in many modern flotation circuits. Unfortunately, the classical methods used in most control strategies have severe limitations when used in froth flotation. For example, the nonlinear nature of the flotation process can cause single-input, single-output lines to battle each other in attempts to achieve a given objective. Other problems experienced in classical control schemes include noisy signals from sensors and the inability to measure certain process variables. Factors related to ore type or water chemistry, such as liberation, froth stability, and floatability, are often difficult or impossible to measure.

The purpose of this project is to demonstrate an advanced control system for fine coal flotation. The demonstration is being carried out at an existing coal preparation plant by a team consisting of Virginia Polytechnic Institute and State University (VPI&SU) as the prime contractor and J.A. Herbst and Associates as a subcontractor. The objectives of this work are: 1) to identify through sampling, analysis, and simulation those variables which can be manipulated to maintain grades, recoveries, and throughput rates at levels set by management; 2) to develop and implement a model-based control strategy that continuously adjusts those variables to maximize revenue subject to various metallurgical, economic, and environmental constraints; and 3) to employ a video-based analyzer for on-line analysis of ash content in fine coal slurries.

Previously, the steady-state and dynamic performance of the flotation bank at the test site (Pittston's Moss No. 3 plant), was characterized as part of Task 2 - Sampling and Data Analysis, and the results of this sampling campaign were reported in the Seventh and Eighth Quarterly Technical Progress Reports. The data collected from Task 2 were then used to construct a

population balance model of the flotation bank at the Moss No. 3 plant (Task 3.1). The details of this work were described in the Eighth Quarterly Technical Progress Report.

During the past quarter, the population balance model was coded into a flotation circuit simulator (Task 3.2) which was then used to evaluate control strategies (Task 3.3). As a result of this work, and after consultation with Pittston management, a control strategy based on maintaining a constant incremental ash in the last cell was deemed most appropriate. It is well known that for a given coal quality, yield is maximized when all circuits in a coal preparation plant are operating at the same incremental ash. Thus, a control strategy based on maintaining constant incremental ash in the last cell will, in effect, maximize yield at an acceptable coal quality. Historical data from flotation circuits operating in the Central Appalachian coal fields indicates that this incremental ash value should be somewhere around 38%.

Concurrent with the evaluation of control strategies, calibration of the video-based ash analyzer (Task 4.1) continued. An operating analyzer is now in place on the tailings stream of the Moss No. 3 flotation bank, and a preliminary calibration curve has been obtained. Unfortunately, the plant has been operating very consistently for the past several months and nearly all of the data points are in excess of 80% ash. Sample collection is continuing in order to increase the range of the calibration.

At present, expert system development (Task 3.4) is now underway, and equipment procurement (Task 6) has begun. It appears that the project is roughly three months behind schedule, but it is expected that some of this lost time can be recovered once the in-plant installation of the control system begins. Control system installation is now scheduled for the week of August 10 and the evaluation of the control system is expected to be conducted from September through November.

INTRODUCTION

Over the past thirty years, process control has spread from the chemical industry into the fields of mineral and coal processing. Today, process control computers, combined with improved instrumentation for monitoring process parameters and performance, have demonstrated improved control in many modern flotation plants. Unfortunately, the classical methods used in most control strategies have severe limitations when it comes to control of froth flotation. The nonlinear nature of the flotation process, for example, can cause single-input, single-output control lines to battle each other in attempts to achieve a specific control objective. Other problems experienced in classical control schemes include noisy signals from measuring devices and the inability to measure certain process variables. Furthermore, factors related to ore type or process water chemistry, such as liberation characteristics, froth stability, and floatability, cannot be measured by conventional means.

The purpose of this project is to demonstrate an advanced control system for fine coal flotation at an operating coal preparation plant. The objectives of this work are: 1) to identify through sampling, analysis, and simulation those variables which can be manipulated in the plant to maintain grades, recoveries, and throughput rates at levels set by management; 2) to develop and implement a model-based computer control strategy that continuously adjusts those variables to maximize revenue subject to various metallurgical, economic, and environmental constraints; and 3) to employ a video-based optical analyzer for on-line analysis of ash content in fine coal slurries. The following is a summary of work completed during the ninth quarter of this project.

TECHNICAL DISCUSSION

Task 1 - Project Planning

Project planning during the past quarter focused primarily on monitoring the efforts of the subcontractor (J.A. Herbst and Associates) in performing Task 3 (Model Building and Computer Simulation), and directing the continued work on calibrating the video-based ash analyzer (Task 4).

Task 2 - Sampling and Data Analysis

This task has now been completed.

Task 3 - Model Building and Computer Simulation

The purpose of this task is to use the data from Task 2 to produce a dynamic model of the flotation circuit for testing control strategies and implementing a model-based control scheme.

Subtask 3.1 - Model Building: This subtask has now been completed.

Subtask 3.2 - Simulator Development: The model developed under Subtask 3.1 was incorporated into a dynamic flotation bank simulator written in the C++ language. The use of C++ makes it possible to create object-oriented code which is more robust and amenable to future modification. In addition to the flotation bank object, a generic Kalman filter object was coded for use in on-line parameter estimation for the model. Finally, an optimization object was included to provide a mechanism for on-line optimization of the control strategy.

Subtask 3.3 - Control Strategy Evaluation: The greatest strength of model-based control is that it allows powerful decision making based on quantitative on-line estimates of floatability changes in the plant, and accurate predictions of the impact of changes in manipulated variables. The Moss No. 3 plant objective is to maximize incremental ash

without exceeding 38%. This figure was arrived at through consultation with Pittston personnel, and is financially driven. The control system that is being developed as part of this project will use the flotation model to maintain incremental product ash as close to 38% as possible. This will be done by maximizing the quantity:

$$\left[\frac{d(\% \text{Ash } \% \text{Yield})}{d(\% \text{Yield})} \right]_{\text{Last Cell}} = f(\text{Frother, Collector, Level}) = A_i \quad (1)$$

with respect to the manipulated variables of frother, collector, and level on a moment-to-moment basis. Equation 1 is a continuous definition of incremental ash which is equivalent to the common discrete form given by:

$$A_i = \frac{A_n Y_n - A_0 Y_0}{Y_n - Y_0} \quad (2)$$

where A_i , A_0 , and A_n are incremental, old, and new ash, respectively, and Y_0 and Y_n are old and new yield. Additional control strategies may be tested, but this is the most desirable strategy from Pittston's point-of-view.

Incremental ash will be estimated on-line based on the model equations developed under Subtask 3.1. These equations were simplified from the original population balance model to give the following expressions for yield and ash:

$$Y = \sum_{j=1}^3 \left[1 - \left(\frac{1}{1 + k_{A,j} t} \right)^N \right] f_{A,j}^F + \sum_{j=1}^3 \left[1 - \left(\frac{1}{1 + k_{C,j} t} \right)^N \right] f_{C,j}^F \quad (3)$$

$$A = \frac{1}{Y} \left(\sum_{j=1}^3 \left[1 - \left(\frac{1}{1 + k_{A,j} t} \right)^N \right] f_{A,j}^F \right) \quad (4)$$

where $k_{A,j}$ is the flotation rate constant for ash in the j -th size class, $k_{C,j}$ is the flotation rate constant for coal in the j -th size class, $f_{A,j}^F$ is the weight fraction of ash in the j -th size class in the feed, $f_{C,j}^F$ is the weight fraction of coal in the j -th size class in the feed, and τ is the mean residence time. It should be noted that the original population balance model reduces to the popular mixers-in-series model after appropriate simplification. Thus, N represents the number of mixed tanks in the flotation bank, which, in this case, is approximately 4 based on previously reported RTD data.

The dependencies of $k_{A,j}\tau$ and $k_{C,j}\tau$ on manipulated variables (level L , collector C and frother F) were obtained from empirical relationships also established under Subtask 3.1. These relationships have the form:

$$k_{i,j}\tau = k_i\tau \left(\frac{d_j}{d_1} \right)^b \left(1 + a_{i,L}dL + a_{i,C}dC + a_{i,F}dF \right) \quad (5)$$

where i is the species (i.e., ash or coal), d is particle size, and α and β are fitting constants. The values obtained by linear regression are:

Species i	b	$k_i\tau$	$a_{i,L}$	$a_{i,C}$	$a_{i,F}$
Coal	1.1	2.012	0.0561	-0.0578	-0.0278
Ash	1.1	0.245	0.3356	-0.1646	-0.0367

As a check on model validity, predictions from the model equations were compared against data obtained at Moss #3 during Task 2. The computed values of $Y = 69.2\%$ and $A = 8.66\%$ compare favorably with experimental values of $Y = 72.1\%$ and $A = 9.17\%$.

Figure 1 shows yield and ash values calculated using Equations (3) and (4) for different pulp levels (frother, collector and feed composition were assumed constant).

Also shown in Figure 4 are incremental ash values as calculated from Equations (3) and (4) in conjunction with Equation (1). As shown, the predicted trends appear to be in agreement with common expectations.

Figure 1. Total yield and percent ash from fitted model.

Figure 2. Incremental ash from fitted model.

Based on the model discussed above, the control strategy to be employed in this investigation is given as follows:

- 1) Set incremental ash objective.
- 2) Read tailings ash from the Virginia Tech Ash Analyzer.
- 3) Estimate floatability ratio (i.e., k_C/k_A) with model and Kalman filter.
- 4) Calculate level setpoint change to achieve the objective incremental ash value.

This strategy is currently being evaluated via computer simulation using the approach illustrated in Figures 3 and 4. Here the incremental ash objective is set at 38%. An on-line analysis is taken at the current pulp level of 64 inches, and the refuse ash is determined to be 65.1%. The floatability ratio of the current feed coal is estimated to be 10.2, which is used to calculate the pulp level setpoint change, $dL = 1.8$ inches, required to achieve the target incremental ash. It should be noted that throughout this scenario, it is assumed that the feed composition remains constant between shift analyses, since there is no on-line analysis of the feed.

Figure 3. Obtaining floatability ratio from online ash analysis.

Figure 4. Model based level setpoint change to achieve target.

Subtask 3.4 - Expert System Development Expert rules are currently being added to the above control strategy to insure that no emergencies exist and that the ash measurements are reasonable and control actions are not too large. It is expected that this task will be completed by the end of July, 1998.

Task 4 - Sensor Testing

Subtask 4.1 - Calibration Testing: During the past quarter, a video-based ash analyzer was installed on the tailings stream of the flotation bank at the Moss No. 3 plant site (see Figure 5). The system is essentially the same as that used at the Middle Fork site and includes: a sample presentation tube inserted in a small sump, a fiber optic illuminator to provide a controlled light source for the images, and a personal computer with frame grabber board to process the images. A line conditioner is used to ensure that line voltage fluctuations do not affect the sample illumination.

Figure 5. Schematic of the video-based ash analyzer installed on the flotation bank at Pittston's Moss No. 3 preparation plant.

Calibration tests were carried out during this same time period and the results are shown in Figure 6. As shown, there is a definite trend showing increasing gray level with increasing ash content. Unfortunately, of the 26 data points collected, 24 are greater than 80% ash. Thus, the range of the data is very limited and, as a result, the accuracy is deceiving. The ash analyzer is now operating continuously, on-line, and calibration testing is continuing in order to collect a wider range of data. In addition, work is being carried out to modify the graphical user interface to conform to the specifications of Pittston management.

Subtask 4.2 - Design and Fabrication: This subtask is essentially complete barring any changes suggested by continued calibration testing at the Moss No. 3 site.

Task 5 - Sample Analysis and Characterization

Sample analysis is continuing as samples are collected under Task 4. All sample analysis and characterization work is on schedule.

Figure 6. Preliminary calibration curve for the video-based ash analyzer at the Moss No. 3 preparation plant.

Task 6 - Equipment Procurement and Installation

Following the calibration testing of the video-based ash analyzer, carried out under Subtask 4.1, specifications for the system to be installed as part of the Moss No. 3 control system were established and all parts have now been ordered and installed. Equipment specifications for the control system have been established as a result of the outcome of Subtask 3.3 (Control Strategy Evaluation). All control equipment has now been ordered with expected arrival and installation of this equipment in July and August. Any additional equipment requirements are expected to be minor pending local needs during installation.

Task 7 - Operation and Testing

Due to delays in completing Task 3, this task will likely be delayed until August, 1998.

Task 8 - System Evaluation

Due to delays in completing Task 3, this task will likely be delayed until August, 1998.

Task 9 - Decommissioning

This task is scheduled to begin in January, 1999.

Task 10 - Final Report

This task is scheduled to begin in February, 1999.

SUMMARY STATUS AND FUTURE WORK

Major accomplishments during the past quarter were the completion of Task 3 (Model Building and Computer Simulation) with the exception of expert system development (Task 3.4) and completion of Task 4 (Sensor Testing) with the exception of on-going calibration testing to increase the calibration range. As a result of this work, the following conclusions can be drawn:

1. Simulator development and control strategy evaluation have been completed. A control strategy of maximizing incremental ash off of the last flotation cell, up to a maximum of 38%, has been agreed upon with Pittston personnel as the primary control strategy to be investigated in this project.
2. A preliminary calibration curve for the video-based ash analyzer has been established showing an excellent correlation between mean gray value and percent ash. The range of the calibration needs to be increased to improve the accuracy and reliability of the sensor.

Work is progressing well, and it appears that the delay caused by switching test sites has only set the project back by three months. It is expected that the control system installation work under Task 6 will be carried out in the middle of August, and the actual operation and testing of the control system (Task 7) will be carried out from September through November. This should make it possible to bring the project back on schedule and complete all work within the original time frame.

NOMENCLATURE

A	- ash content
A_i	- incremental ash
A_n	- new ash value
A_0	- old ash value
C	- collector
d	- particle size
F	- frother
$f_{A,j}^F$	- weight fraction of ash in the j -th size class in the feed
$f_{C,j}^F$	- weight fraction of coal in the j -th size class in the feed
i	- assay class
j	- size class
$k_{A,j}$	- flotation rate constant for ash in the j -th size
$k_{C,j}$	- flotation rate constant for coal in the j -th size class
L	- level
N	- number of mixers in series
Y_0	- old yield
Y_n	- new yield
Y	- yield
α	- fitting parameter
β	- fitting parameter
τ	- mean residence time