AN EXPERT SYSTEM APPLICATION FOR LIME KILN AUTOMATION

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Abstract - The complex nature of the lime calcining process with its long time delays, variable feed characteristics, changing operating conditions, non-linear chemical and thermal reaction rates makes the rotary lime kiln difficult to operate. The time dependent and complex interaction between kiln parameters makes the successful automation of kiln operation a daunting task that has eluded many kiln operators.

This paper describes a kiln automation system that combines an expert system with adaptive loop controllers to automate kiln operation and provide significant kiln performance improvements.

INTRODUCTION

The goals of lime kiln automation are:

- improve lime quality
- increase kiln production
- improve fuel efficiency
- increase refractory life
- improve kiln information gathering and processing.

In most lime kilns these goals are not being met because:

- process sensors are unreliable and inaccurate,
- the instrument loop controllers used cannot maintain the process variables at the set points,
- accurate, dynamic kiln process models that can automatically calculate and adjust kiln set points to produce quality lime at optimum efficiency have not been developed,
- kiln operators have varying and sometimes conflicting operating methods that prevent efficient and stable kiln operation from one shift to the next,
- long process time delays, particularly with respect to product temperature control, make operation of the kiln difficult because operators must remember their past actions for several hours in order to correctly interpret current kiln conditions.

Many of the problems facing kiln automation can be corrected by using present technology and by maintaining process sensors and equipment in good working order. However, there are certain kiln control loops such as the firing hood draft whose characteristics are beyond the capability of conventional process controllers. Kiln operators generally turn such loop controllers to the manual mode and close the loop themselves. Most operators have difficulty handling the long time delays inherent with lime kiln operation. In addition, they often use unsuitable control tactics. The net result is less than optimal kiln operation and lime quality, and production efficiency suffers.

The lack of kiln automation can significantly limit kiln performance.

This paper describes a new approach to lime kiln automation that combines the experience of lime kiln operators in an expert system program with a unique adaptive process loop controller to achieve the long sought goals of kiln automation.

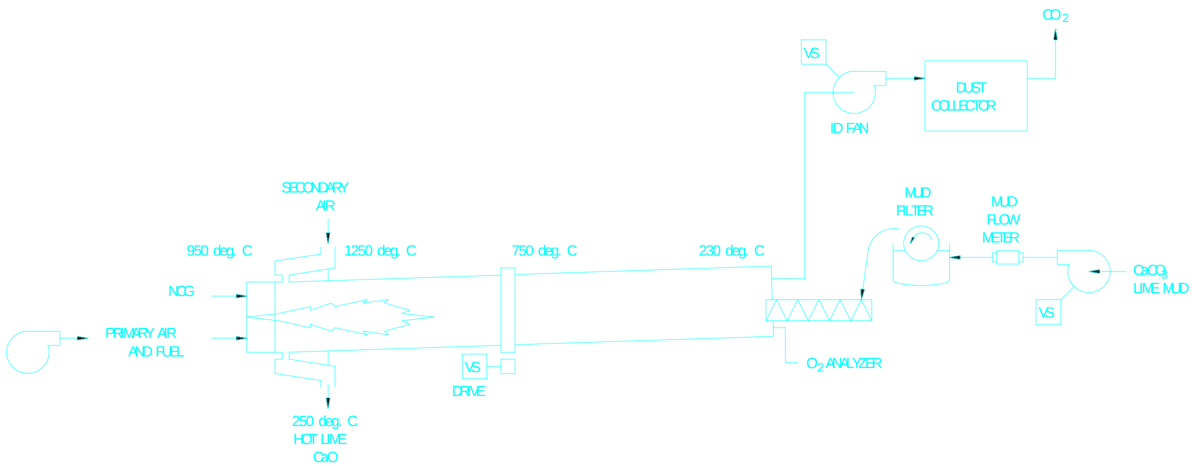

Figure 1. Typical Pulp Mill Lime Kiln

DESCRIPTION OF KILN OPERATION

The rotary lime kiln is a major component of the kraft pulp mill recausticizing operation. Sodium hydroxide, which is mixed with the wood chips and cooked in the digester, is recovered in the recovery boiler and regenerated in the recausticizing plant. This is done by exchanging the sodium ion in the green liquor (sodium carbonate stream) from the recovery boiler with a calcium ion from calcium hydroxide. After the exchange, sodium hydroxide is mixed with wood chips in the digester and the calcium carbonate is calcined to form CaO in the rotary kiln. The calcium oxide is then slaked to form calcium hydroxide. The calcium hydroxide is mixed with the sodium carbonate from the recovery boiler and the whole cycle is repeated.

The lime calcining process used by most kraft pulp mills uses a rotary lime kiln to convert the calcium carbonate mud from the clarifiers to quick lime or calcium oxide. A typical kiln installation is shown in Figure 1.

It consists of a mud filter where the moisture content is reduced to about 30 to 35%, a rotary kiln and dust collector. The kiln itself is generally thought to consist of three sections. The first section is a preheater or chain section where the calcium carbonate mud is dried and nodulized. The second section is a calcining zone where the feed is heated to about 1150°C and converted to calcium oxide. Some kilns have a third section where the quick lime is cooled and the secondary combustion air is preheated. In most cases, the cooler consists of a number of tubes arranged around the circumference of the kiln at the firing end of the kiln. The calcining process is endothermic and requires 3.0 kJ/kg of lime at a temperature in excess of 900°C. Most kilns use natural gas or oil as a fuel source. Some installations use coal as a fuel but there is concern that the ash residue will cause an undesirable build-up of contaminates in the lime, which could adversely affect the quality of caustic produced by the recausticizing plant.

The transit time of the feed through the kiln varies with the production rate but is typically between three to four hours.

In many kilns secondary burners are used to destroy the non-condensable gases (NCG) that are generated in other parts of the pulp mill. These gases are collected and burned in the lime kiln along with the main fuel. The variable heating value of the NCGs causes additional disturbances to kiln operation.

Lime kilns are subject to a number of disturbances and variations, some of which can be measured and some not. Common problems that adversely affect kiln operation are:

- variable mud feed rates due to changing filter action and periodic recoating of the filter cloth,
- varying mud moisture content,
- excessive sodium carbonate ($NaCO_3$) in the mud feed,
- varying flow and heat content in the NCGs burned in the kiln,
- non-linear combustion and lime calcination characteristics,
- manual operation of instrument control loops,
- unreliable operation of kiln instrumentation,
- operator propensity to run kilns in a "comfortable" mode rather than the most efficient mode,
- differing kiln control tactics between one shift and the next, which can cause kiln upsets at each shift change.

KILN AUTOMATION SYSTEM

The kiln automation system was developed to address many of the problems that hinder proper kiln operation. Four elements were identified as being essential for the successful automation of a lime kiln. They are the need for:

- accurate and reliable process sensors for all key kiln parameters,
- instrument loop controllers that will automatically and continuously maintain kiln variables at their set point under all operating conditions. The controllers must be able to handle non-linear process characteristics that change over time and have long time lags,
- a supervisory control system that will adjust the instrument controller set points to maximize production of quality lime using the least possible amount of fuel,
- a production database to analyze kiln performance.

The ability to accurately measure and report kiln performance makes management information readily available and the evaluation of kiln performance possible. It also permits on-line kiln quality control analysis to be carried out and further enhancements in kiln operation to be implemented.

Process Sensors

All the required process sensors have been available on most kilns for a number of years. However, most mills do not have sensors that are accurate and available on a continuous basis. There are several reasons for this situation:

- instruments have not been properly installed to give reliable operation,
- instruments have not been maintained in good working order,
- instrument signals that have a high noise component which most controllers are unable to effectively filter out,
- instruments whose failure mode is not recognized by many lime kiln controllers or operators.

No kiln automation system can function unless all the required sensors are kept in good working order. It is pointless to proceed with a kiln automation project unless there is a commitment to upgrade and maintain the kiln process sensors.

Instrument Loop Controls

An adaptive controller (AC) was developed [1] specifically for use in controlling complex instrument loops on rotary kilns where conventional loop controllers are inadequate. The AC has the unique ability to learn the process characteristics while it is controlling the process. The AC is an adaptive controller that predicts the correct control action to handle process changes. It never needs re-tuning once it has been installed because it continuously adapts to the process characteristic changes. The AC's ability to handle non-linear processes makes it possible to stabilize all the kiln control loops and to leave the controller in the "automatic" mode of operation.

The AC uses a Laguerre function series representation for modeling plant dynamics.

As such, it could also be described as a neural network based controller [2].

Expert System

The purpose of the supervisory control system is to generate optimal set points for the kiln control loops. At the beginning of the development of the kiln automation system, it was intended to use a linear steady state thermodynamic model of the kiln to calculate the various instrument loop set points. Statistical analysis of the kiln operating data would be used to adjust the steady state thermodynamic model of the kiln so that the best kiln operating conditions would be determined. This approach was unsuccessful because measurements of all the variables affecting the thermodynamic model were not available on a consistent enough basis to be able to calculate optimal set points. In addition, field experience indicated that many kilns do not operate in a truly steady state mode for very long. There was a more or less continuous stream of perturbations of varying sizes that inhibited steady state operation. Therefore, the use of a linear steady state model would not be very effective even if all the required parameters could be measured on a regular basis. The use of a dynamic model of the kiln was out of the question as we are unaware of the existence of any such accurate dynamic model. Any dynamic model of kiln operation would have to use higher order non-linear equations for which few realistic solutions exist.

In the original concept of using a steady state thermodynamic model to calculate the kiln set points, it was intended to use a rule-based expert system to handle any "out-of-limits" or emergency kiln situations to either bring the kiln back within limits or to effect an automatic kiln shutdown. Extensive experience in attempting to implement a fixed model-based kiln supervisory control system indicated that this approach was not viable. Therefore, it was decided to emulate the actions of the "best" kiln operator and use a rule-based expert system to provide supervisory control.

The expert system was designed and tested over a period of 1-1/2 years. It was designed to handle normal quasi steady state operation (i.e., able to handle small perturbations) of the kiln with some "rate" features to accommodate some of the larger changes to kiln operating conditions. The "rate" features of the program look at the rate of change to kiln variables in the preceding couple of hours and adjust the size of the calculated set point change accordingly.

Two expert system modules were devised to operate independently of the other. One is called the "Combustion Advisor" and the other the "Production Advisor". The purpose of this approach was to reduce the global problem of kiln automation to two more manageable programs that could logically operate independently.

The Combustion Advisor automatically adjusts the

- fuel firing rate,
- primary air,
- secondary air, and
- firing hood draft

for optimum purchased fuel use as measured by an Oxygen/Combustibles analyzer located at the kiln feed end. The Combustion Advisor automatically accommodates variations in fuel heat values such as are caused by the burning of NCGs in the kiln. The Combustion Advisor tries to increase the fuel consumed by the kiln within the limits (set by the operator) on each of the loops by adjusting set points in a programmed order of priority. The differences between the target O_2 and combustibles readings and the actual readings determine the amount of set point change that is made.[3]

In general, the Combustion Advisor program will maximize heat input to the kiln to the limit set by the operator.

The Production Advisor automatically adjusts the

- lime mud flow rate,
- kiln speed

to maintain a predetermined kiln temperature profile. The kiln temperature profile is selected by the lime kiln operator and is derived by statistical analysis of the relationship between Loss on Ignition (LOI) tests on the lime or reactivity of the lime and the kiln temperatures as measured at the feed end and the firing end. The reactivity and LOI tests are a measure of how completely the $CaCO_3$ is converted to CaO and the degree to which the lime has been burned. Over burned lime has a lower reactivity than soft burned lime. These measurements are some of the common indicators of lime quality

The Production Advisor program takes maximum advantage of the heat available in the kiln to maximize the production of a specific lime quality even though there may be heat input variations and variations in lime mud moisture content.

Production Data Processing

The need for a database to log and store kiln parameters, including operator entered information, is obvious. Before meaningful rules for controlling the kiln can be developed, the relationships between kiln parameters must be analyzed. The analysis can be greatly enhanced by graphing the parameters. A quick visual confirmation or denial of expected relationships is readily seen by comparison of parameter trends. In the longer term, the data is available for shift reporting and trend analysis by the kiln operator during his regular shift. The data is also available for analysis and future enhancements to the expert system rules. A typical graph of kiln parameters used in the development of the kiln automation system is shown in Figure 2.

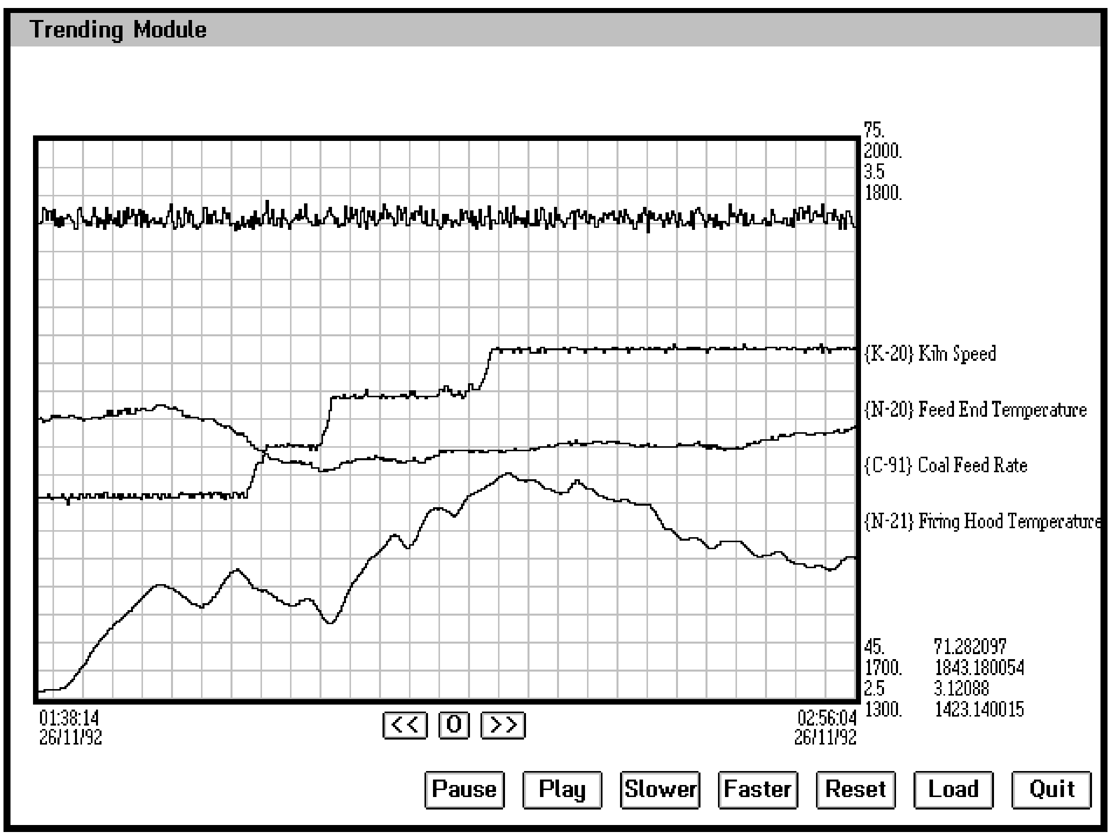

Figure 2. Typical Graph

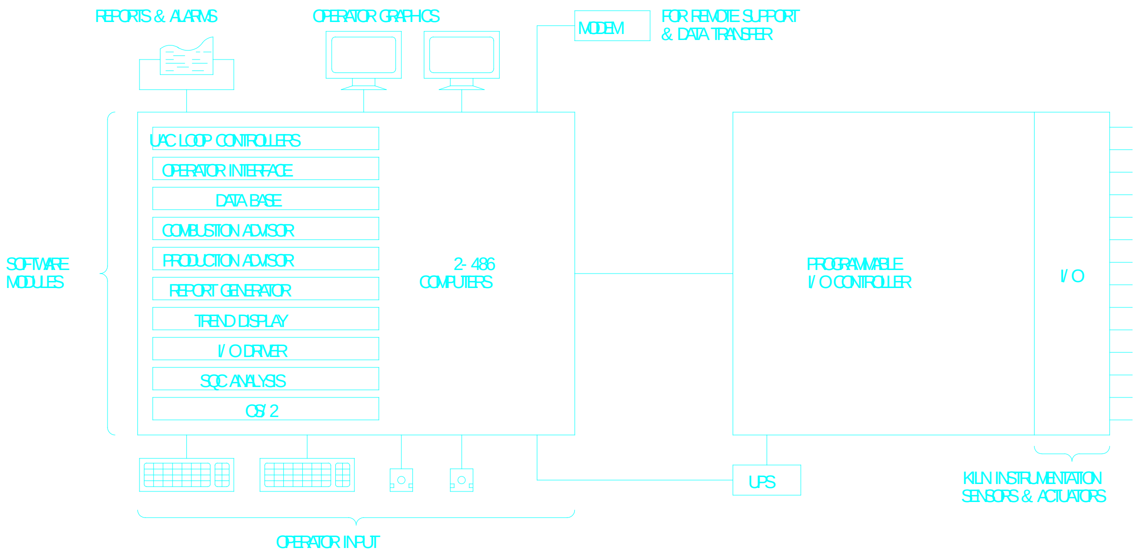

Figure 3. System Configuration Diagram

RESULTS

The kiln automation system was originally developed and installed on a rotary kiln producing pebbled lime from 3/4" by 2" limestone. The kiln was 150 feet long and 12 feet in diameter. The kiln burns coal and has a contact-type stone preheater and lime cooler. The nominal rating of the kiln is 475 T/day at a fuel consumption of 4.9 MBtu/Ton.

The kiln automation system was implemented on a 386 microcomputer and a programmable logic controller. A second 486 computer was added later (see Figure 3).

After the database and parameter trending programming was running, the development of the AC was completed and installed on all kiln control loops. A dramatic improvement in the stability of kiln operation was noticed. Figure 4 shows the operation of the kiln firing hood draft under automatic AC control. Previous use of PID loop control did not keep the firing hood draft stable and the operators used to switch the control to the manual mode within a few days after the PID controller was tuned.

After the control loops were stabilized, an extensive review of the kiln operations was done with the kiln operators to determine the best control strategy. In addition, a number of tests were carried out to determine the effects of various changes to kiln variables such as fuel, combustion air and temperature profile.

An "If/Then" rule-based expert system was used because of its simplicity and ease of implementation. The final configuration of the Combustion Advisor and the Production Advisor used 150 rules and 50 rules respectively. The Production Advisor module was designed to handle two different lime specifications.

Each expert module was installed and tested over a number of months. The kiln operators suggested modification to some parts of each program. The changes were implemented and testing was continued.

The major problems encountered were the lack of reliability in the O_2/Combustibles analyzer and a large number of equipment operating problems that prevented steady operation of the kiln during the testing of the

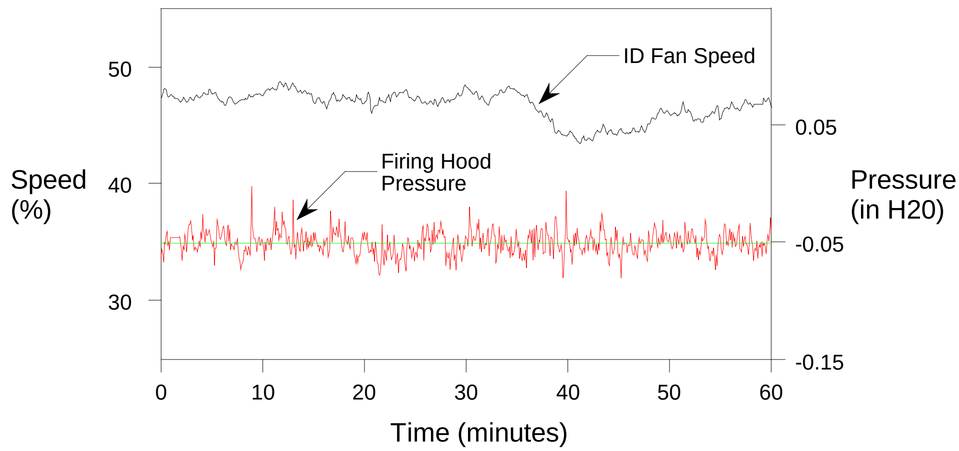

Figure 4. AC Control - Firing Hood Draft

expert system. However, initial test results indicate that:

- the production of on-spec lime increased from 25% to 90%,
- production increased by 10%,
- fuel efficiency increased by about 5%.

No calculation of refractory life increases has been made yet.

For a typical pulp mill lime kiln producing lime at around 200 T/day, the benefits of automation are estimated to be between $500,000 and $1,000,000 per year.

CONCLUSION

An expert system can automate lime kiln operation successfully, provided:

1. accurate, reliable process instrumentation is used and maintained in good working order.
2. loop controllers consistently maintain process variables at their set points regardless of changing process gains and time delays.
3. flexible, easy-to-use process parameter reporting and trending is available to establish the rules for the expert system, to annunciate when program changes may be required and to measure the improvements due to kiln automation.

If any of the preceding three conditions are not satisfied then automatic operation of a lime kiln is not possible.

An expert systems approach to kiln automation allows the unique characteristics of each kiln to be taken into account where previous attempts to build a general purpose mathematical model of the calcining process have proven inadequate. The flexible features of expert system programs allow kiln operators to easily modify the automatic operation of the kiln to accommodate process or equipment changes. The use of one expert system module to control combustion and another expert module to control production permits some of the benefits of automation to be available even when some of the kiln instrumentation is not functioning.

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