PEER REVIEWED

Practical aspects of model-predictive control implementation on an industrial lime kiln

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ABSTRACT

Rotary lime kilns are significant energy consumers. In the past, little attention has been paid to kilns, resulting in poor efficiency and lime quality. With the adoption of stringent environmental regulations and increased competitiveness, the need for improved lime kiln control has become significant.

Lime quality and granular size are primarily determined by the temperature profile along the kiln. Total reduced sulfur (TRS) and energy consumption can be minimized by maintaining the excess oxygen between constraints. A constrained model-predictive control algorithm was implemented on an industrial lime kiln to improve lime quality, decrease energy consumption, reduce maintenance cost, and eliminate TRS emissions. The control strategy is successful in controlling the temperature profile along the kiln while respecting the constraints in excess oxygen and in the manipulated variables. The strategy is also successful in controlling the temperatures during recurrent upset conditions caused by regular washing of the lime mud filter.

Application:

The model-predictive control technique is well suited to handling highly interactive multivariable processes, such as the lime kiln described in this paper. The strategy is successful in controlling the temperature profile and maintaining excess oxygen with constraints for improved lime quality and energy consumption.

INCONSISTENT LIME QUALITY, AN unstable temperature profile, and reduced sulfur emissions were among the driving forces leading to the need for an improved lime kiln control strategy. The objectives of the strategy are to control the temperature of the solids and the temperature of the exit flue gas to produce good lime quality while maintaining the excess oxygen in the flue gas within lower and upper limits. Excess oxygen is required for complete combustion and to oxidize sulfur compounds in order to avoid the formation of reduced sulfur compounds. These gases, which are malodorous, are subject to environmental regulations. However, it is essential to keep excess oxygen to a minimum for energy efficiency. This will result in improved white liquor production and reduced energy costs, refractory wear, and environmental emissions.

Traditionally the variables are paired and controlled by proportional integral derivative (PID) controllers. Improvements have been made by applying dynamic decouplers. However, the performance of these controllers suffers from inadequate constraint handling. To alleviate these limitations, a model-predictive controller with input and output constraints was implemented. The algorithm is a natural choice, since process limits can be specified explicitly and because the algorithm can handle the lack of degree of freedom to control the process.

THE PROCESS

The chemical recovery section of the kraft pulping process is as important as the pulping process itself. To be economically viable, the cooking liquor (white liquor) used in the pulping process must be regenerated. The toxicity of the spent cooking liquor (black liquor) prohibits its discharge into the environment. The lime kiln is an essential component of the kraft recovery and causticizing operation.

White liquor is an aqueous solution composed mainly of sodium hydroxide (NaOH) and sodium sulfide (Na_2S) *(1)*. Reacting with wood, the white liquor becomes black liquor, which is now mainly composed of Na_2CO_3, Na_2SO_3, Na_2SO_4, and $Na_2S_2O_3$, with residual amounts of NaOH and Na_2S. The causticizing operation uses lime (CaO) to regenerate NaOH from sodium carbonate (Na_2CO_3) according to Reactions 1 and 2 (shown as follows) and produces lime mud, primarily calcium carbonate ($CaCO_3$) as a by-product.

$$CaO + H_2O \Leftrightarrow Ca(OH)_2 \qquad (1)$$

$$Na_2CO_3 + Ca(OH)_2 \Leftrightarrow 2NaOH + CaCO_3 \qquad (2)$$

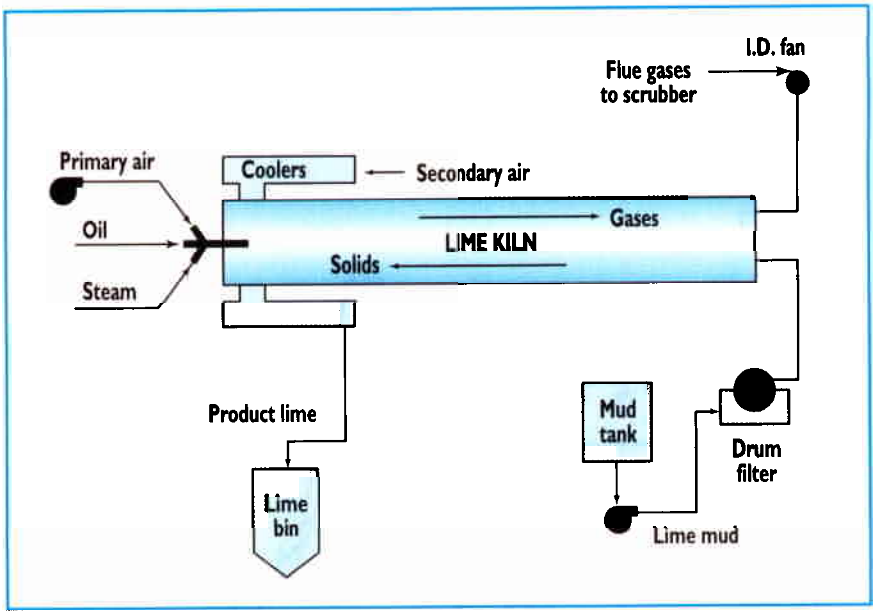
The role of the lime kiln is to recover CaO from the $CaCO_3$ produced by the calcining reaction (3).

$$CaCO_3 + \Delta H \Leftrightarrow CaO + CO_2 \qquad (3)$$

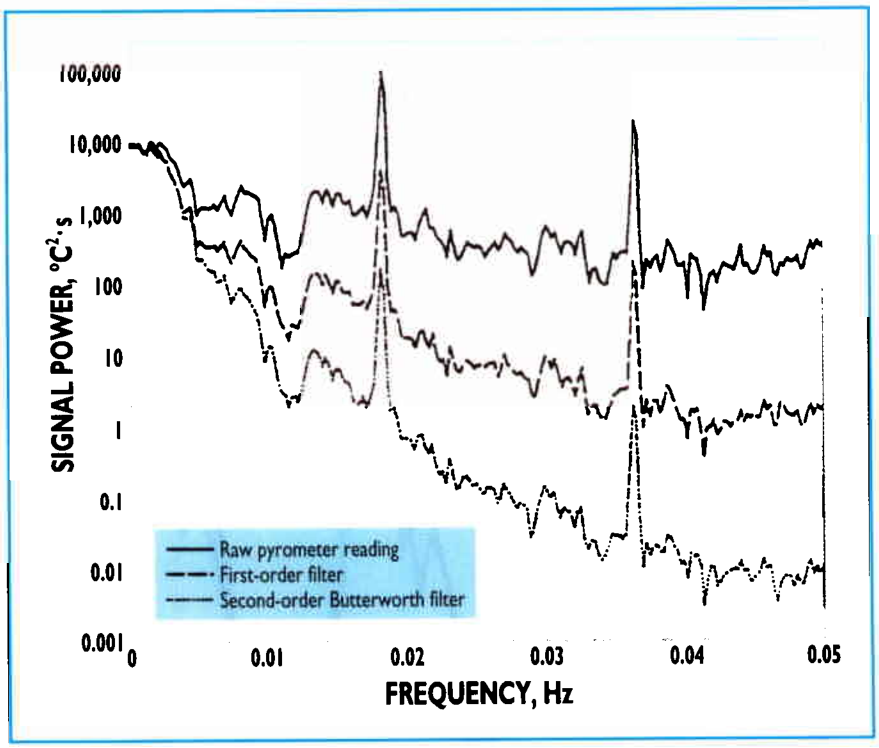
The heat of reaction of calcining, ΔH, is 1786 kJ/kg of $CaCO_3$. A temperature of at least 800°C is required for calcination to proceed.

The lime kiln is essentially a large revolving steel tube lined with refractory bricks. The kiln is 3.2 m in diameter (inside shell) and 67 m long, mounted horizontally with a slight slope of 2°. **Figure 1** illustrates the process. A rotary drum vacuum filter is used to wash out sodium components and dewater the lime mud, which is conveyed to the feed end at about 70% solids. Lime mud travels to the discharge end due to the inclination and rotation of the kiln. Retention time is determined by the rotational speed and the angle of inclination. At the discharge end, burning oil provides heat to the process. Hot combustion gases transfer heat to the solids as the solids are drawn countercurrently by an induced draft fan. At the feed section, heavy chains attached to the interior walls provide a mean of retaining heat and increasing heat transfer to the solids. Six coolers allow cooling and discharge of the solids, while countercurrent secondary combustion air is preheated.

The kiln can be divided into three sections. First, in the drying section located at the feed end, water contained in the solids is evaporated. Good control of the drying rate is required to obtain proper granulometry. Second, in the heating section, the solids are brought to a temperature of about 1200°C. Finally, in the calcination section, the reaction proceeds: $CaCO_3$ dissociates into CaO with the release of CO_2. The extent of the reaction, and thus the quality measurement of lime, is determined by measuring the amount of unconverted $CaCO_3$ left in the solids *(2)*.



1. The calcination process

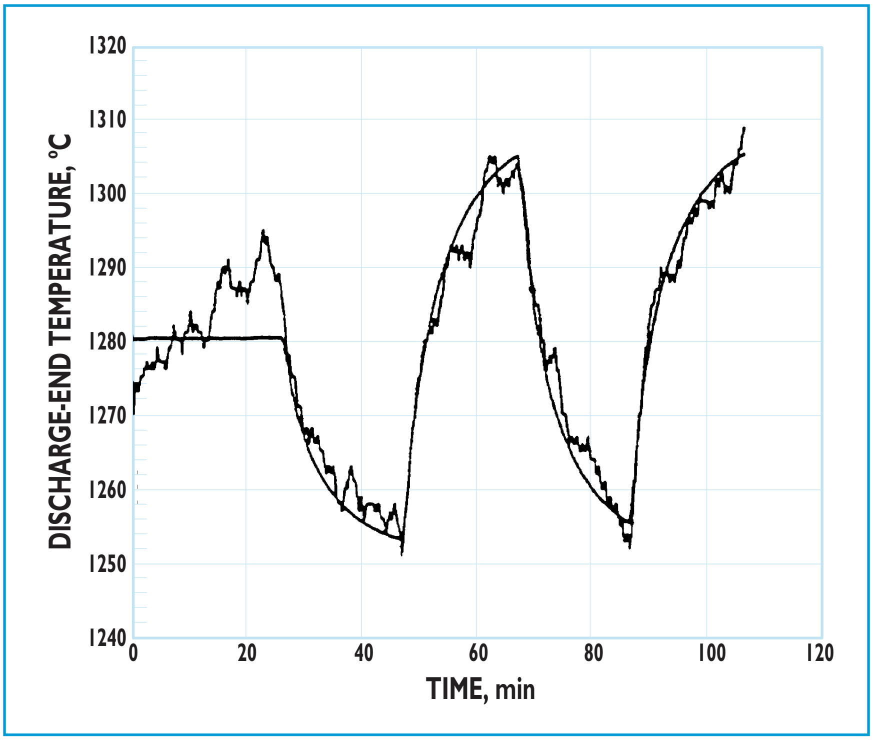


2. Power spectrum of the pyrometer signal

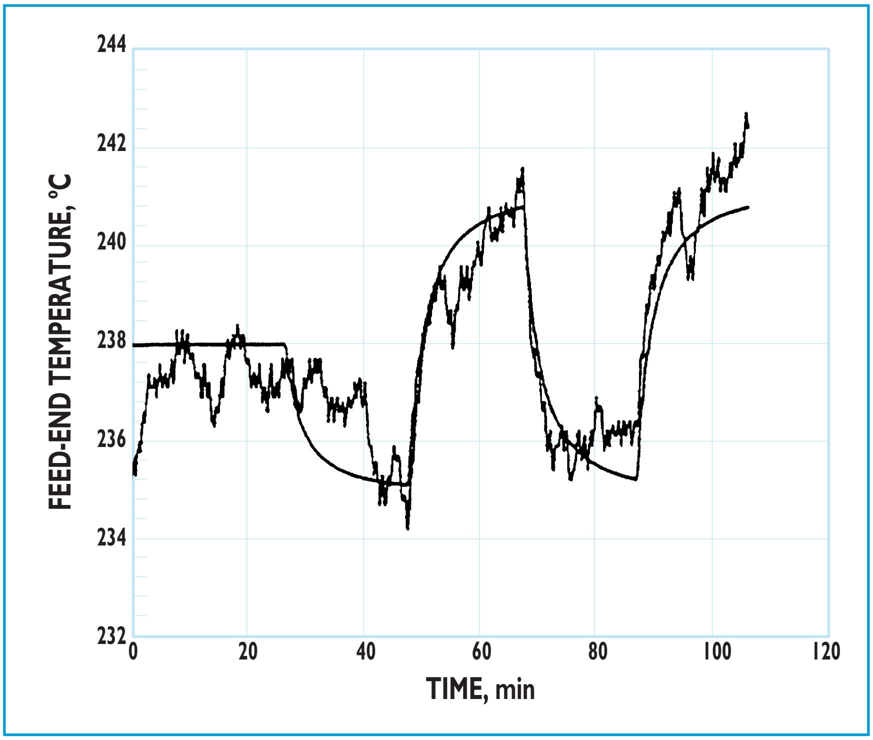
THE CONTROL PROBLEM

Overcalcined and undercalcined lime can both negatively impact the slaking and causticizing operations. Underburned lime produces a deadload that results in increased energy consumption and reduced equipment efficiency. Overburned lime, on the other hand, has poor slaking and causticizing properties. Experience has proved that targeting for residual calcium carbonate of 1-2% results in good lime reactivity.

Good operation of the kiln requires tight control of its temperature profile. This is achieved by controlling the temperature at both ends. An infrared pyrometer measures the temperature of the solids at the discharge end, while a thermocouple measures the temperature of the gases at the feed end. To control the temperatures, two manipulated variables are available: the fuel flow rate and the induced draft fan damper position. Fuel is mixed with primary air and atomized with steam in the burner. Flame shape, regulated by primary air flow, has considerable impact on combustion and heat transfer efficiency in the flame zone. Excess oxygen of the gases is measured at the feed end. Because sulfur is present in significant amounts in



3. Discharge-end temperature response to fuel flow changes. Model vs. process response.



4. Feed-end temperature response to fuel flow changes. Model vs. process response.

the fuel burned and in the solids, a minimum amount of excess oxygen must be maintained. This oxygen ensures complete oxidation of sulfur and avoids emissions of reduced sulfur compounds such as H_2S.

The feed-end temperature setpoint is determined based on operating conditions to complete drying in the drying zone and to maximize efficiency. The discharge-end temperature setpoint is determined based on the requirement of the calcination reaction and the amount of residual calcium carbonate.

The specification of the mud flow rate depends on the availability of stored mud and the desired lime production rate.The mud flow rate is separately managed by a dedicated PID controller. The density of the mud is treated as an unmeasured disturbance. Solids density is controlled at the inlet of the lime mud filter. However, solids density at the outlet gradually decreases as the filter screen becomes plugged. Every 12 hours, the filter is stopped to be washed. During this time, no lime mud is fed to the kiln.This represents the most important disturbance to the process.

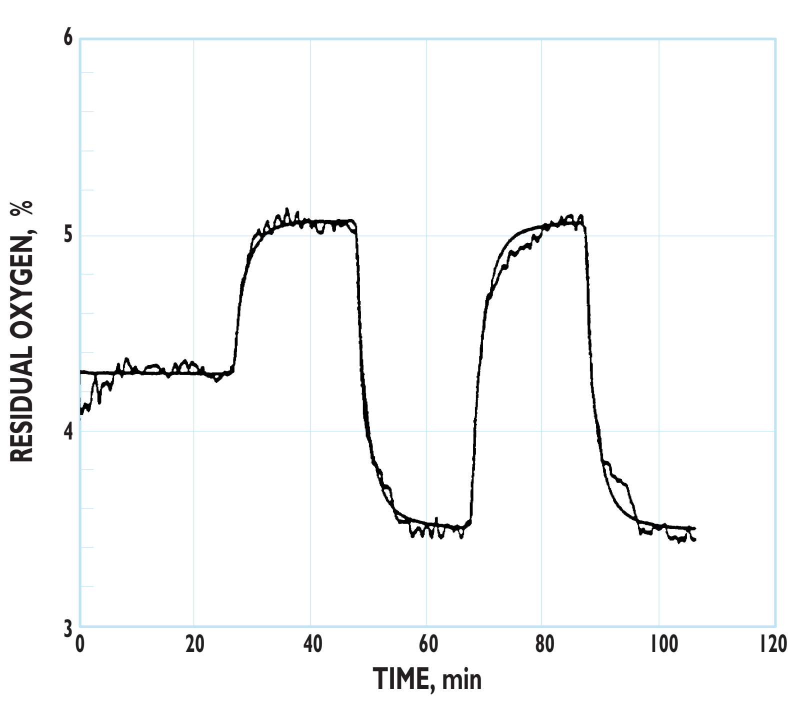
The kiln is a difficult process to control. It is a multivariable process with strong interactions between variables.There are two manipulated variables (damper position and fuel flow) and three controlled variables (feed-end temperature, discharge-end temperature, and excess oxygen). The kiln is characterized by long transport delays, long response times, nonlinearities, noisy measurements, and frequent disturbances.

Traditionally, the temperature profile of the lime kiln is controlled by two independent PID controllers. The best pairing of controlled and manipulated variables is achieved by coupling the solids temperature with the energy source and the exit flue gas temperature with the induced draft fan damper position *(3)*. However, this arrangement usually fails due to the presence of large interactions between the loops, which bring an unstabilizing effect. Improvements have been made by adding dynamic decouplers to cancel the interaction between the loops. Several papers describe successful applications of this type of strategy *(4, 5)*. However, the performance of these controllers suffers from several limitations. Large delays are poorly handled by PID controllers and yield unfeasible decouplers. Inadequate constraints handling forces the designer to add several pieces of logics. Tuning and maintenance are very difficult due to the decentralized nature of a complex PID controller arrangement.

Process output	PROCESS INPUT		
	Designation*	Fuel flow, L/min	Damper position, %
Discharge-end temperature, °C	K	50	–1
	τ	20	20
	θ	2	2
Feed-end temperature, °C	K	5	–8
	τ	15	12
	θ	1	1
Excess oxygen, %	K	–0.5	1
	τ	3	3
	θ	0	0

*K = gain; τ = time constant, min; θ = delay, min

I. Process models



5. Excess oxygen response to fuel flow changes. Model vs. process response.

MODEL PREDICTIVE CONTROL

The model predictive control technology used for control of the lime kiln is a software package that is commercially available for designing and implementing multivariable model-predictive constraint control. The controller uses impulse weight models to predict the future response of the process. It then uses this prediction in an optimization algorithm to minimize (a) the sum of squares of errors and (b) the manipulated variables moves over the prediction horizon p. The optimization problem is formulated to incorporate constraints. The objective function is outlined in Eqs. 4 and 5. The algorithm has only one tuning parameter for each controlled and manipulated variable, Γ^y and Γ^u, respectively. The controller can be designed to handle loss of any combination of manipulated variables and still continue to control the process. A more detailed description of the control algorithm can be found in the literature *(6, 7)*.

$$\min_{\Delta U(k)} \left\{ \sum_{k=1}^{p} \| \Gamma^y [Y(k+1\,|\,k) - R(k+1)] \|^2 + \sum_{k=1}^{m} \| \Gamma^u \, \Delta U(k) \|^2 \right\} \quad (4)$$

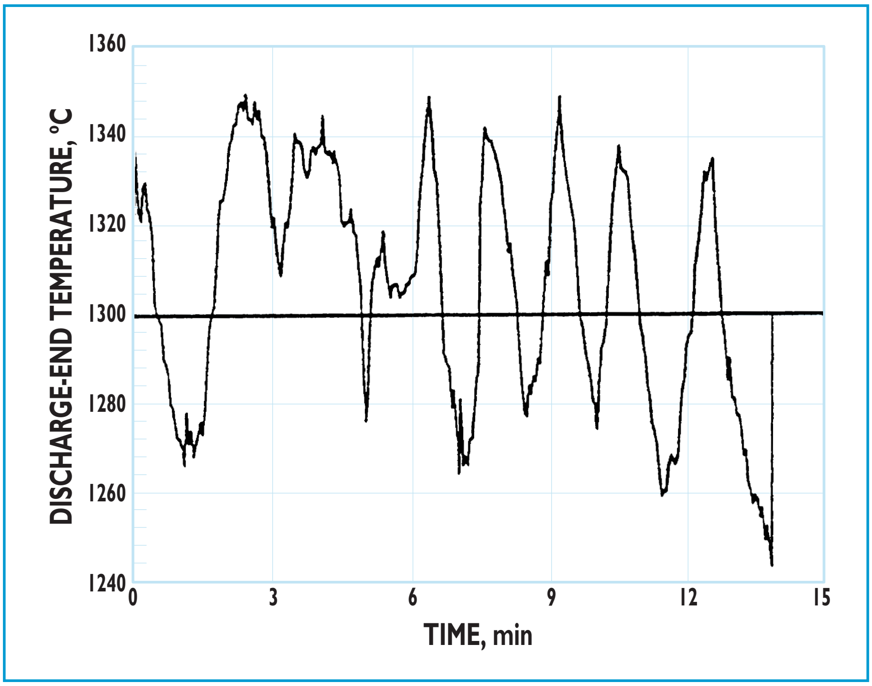
subject to

$$\underline{Y} \le Y(k+1|k) \le \overline{Y}$$
$$\underline{U} \le U(k+1|k) \le \overline{U}$$
$$\underline{\Delta U} \le \Delta U(k+1|k) \le \overline{\Delta U}$$
$$\text{for } k = 1, \ldots, p \quad (5)$$

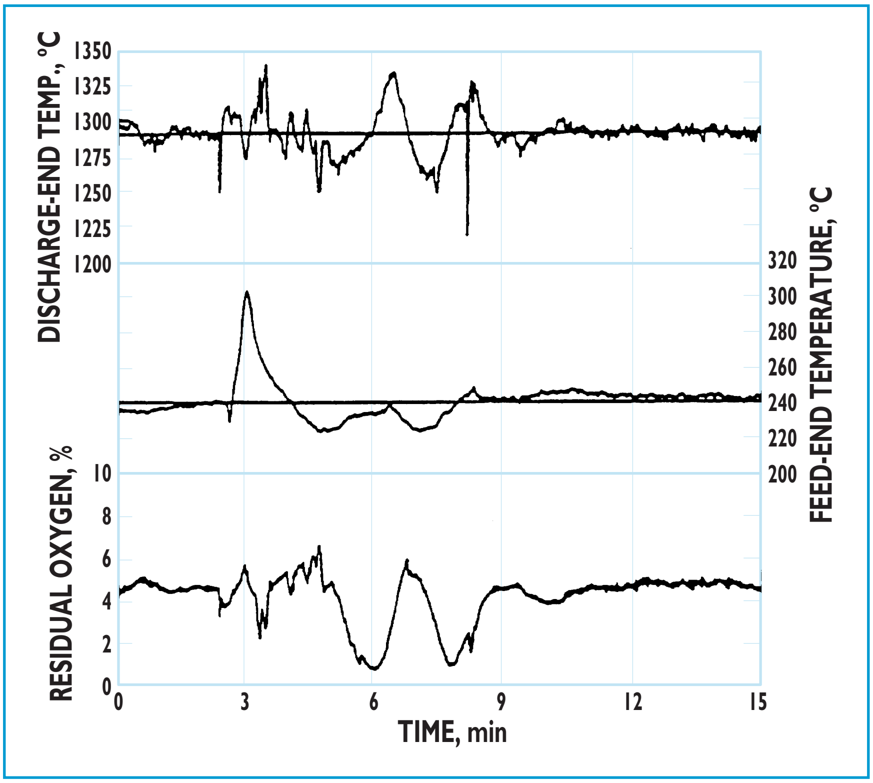
IMPLEMENTATION

Advantages of model-predictive control

Model-predictive control (MPC) is a mature technology in the petroleum and chemical industries. However, very few applications exist in the pulp and paper industry. This technology has several advantages over classical control techniques, such as dynamic decoupling. The same algorithm can be used for a wide variety



6. PID control mode



7. Lime kiln control using MPC. Controlled variables response.

of multivariable control problems. Process constraints are handled explicitly. Due to its centralized nature, the controller is easier to tune and maintain than a set of interacting PID controllers.

Instrumentation

Any control strategy relies on the availability of proper information. Many control strategies have failed due to improper instrumentation or measurements. Our first step in implementing MPC was therefore to check and correct the temperature and excess oxygen measurements. Great care was required to have a reliable pyrometer reading. The measurement noise was reduced with the proper installation, which aimed the pyrometer at the solids and avoided dust and flame interference. However, dust interference also requires adequate signal filtering.

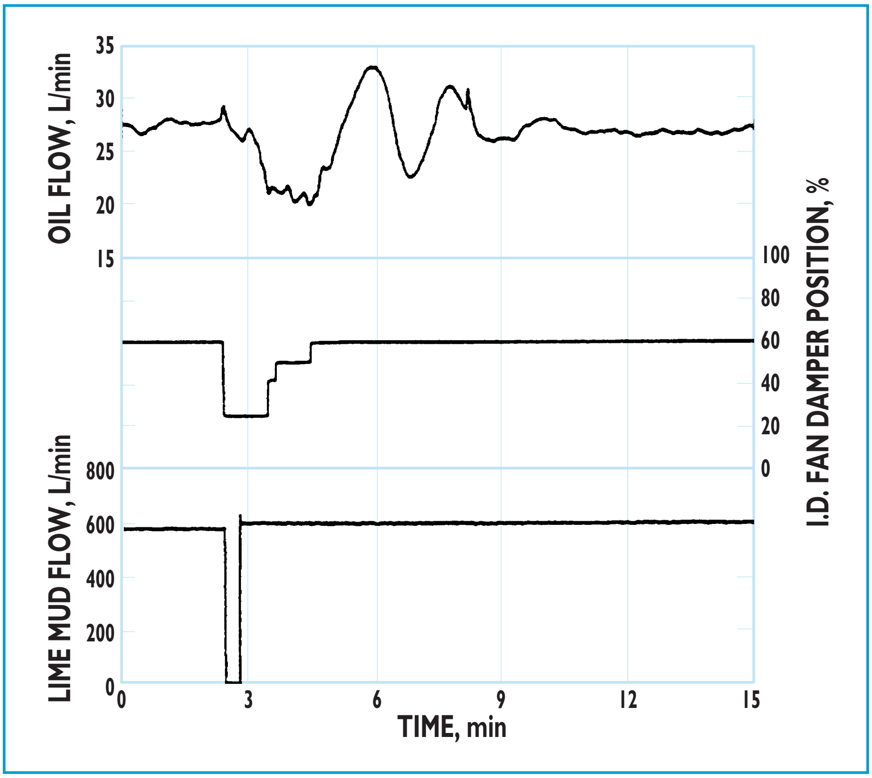
Figure 2 illustrates the power spectrum of the discharge-end temperature. The raw signal spectrum clearly indicates a component at a frequency that coincides with the rotational rate of the kiln, 1 rpm. This component is due to dust and lime rocks falling back from a cooler that reached the upper position. We used a second-order Butterworth filter on the pyrometer to attenuate this effect without imposing a significant dynamic on the signal.

Process identification

Disturbances affect the process frequently. Models needed for the predictive controller were obtained by performing series of identification experiments based on pseudo-random binary sequences (PRBSs). These experiments were designed from step response tests and operating knowledge of the process. **Figures 3–5** illustrate the results obtained. Fuel flow was varied between 25.5 and 28.5 L/min, following a predetermined PRBS. **Table I** summarizes the results of the identification experiments used for MPC.

After performing numerous identification experiments, we developed a few basic rules:

- Determine the complete PRBS before implementing it to ensure its frequency content is appropriate.
- Explain to the operator what you are doing.
- Avoid doing tests in periods of disturbances.
- When a test is in progress, you should be able to see process responses.
- Avoid manipulating more than one variable at the same time.



8. Lime kiln control using MPC. Manipulated variables response.

RESULTS

The model-predictive control strategy is successful in controlling the temperature profile along the kiln while respecting the constraints in excess oxygen. Under normal circumstances, the temperatures are controlled within 20°C at the discharge end and within 5°C at the feed end, as compared to variations of 50°C and 20°C, respectively, with the PID control strategy. **Figure 6** shows the discharge-end temperature under normal operation with the previous PID control. It shows large variations (50°C) due to the inability of the PID controller to compensate for the delay and the interactions of the other process variables. **Figures 7 and 8** show 15 hours of operation to illustrate how the MPC controller performs in a worst-case situation.

The I. D. fan damper was left in manual mode, so the controller could only manipulate the fuel flow rate. Slightly before the 3-hour mark, the lime mud feed was interrupted completely for 30 min to wash the lime mud filter. At the same time, the operator closed the damper by 40%. The disturbance in the feed-end temperature is due to the fact that there is no lime mud to absorb the heat from the gases. The controller handles the disturbance caused to the discharge-end temperature relatively well.

We observed a variation of 30°C compared to a variation of 75°C when the same disturbance is handled with the PID controller. However, the most important disturbance to the discharge-end temperature comes approximately 3 hours later when the gap in lime mud feed reaches this section. At that point, the pyrometer reads a thinner layer of lime, which has received more heat.

To make things more interesting, the operator cleaned the pyrometer without informing the controller as the controller had not completely stabilized the process. However, this did not significantly affect the operation due to the short duration of this upset. Throughout the feed interruption disturbance, the predictive controller successfully maintained the excess oxygen above the lower limit, which was set at 1% to avoid TRS emissions. The controller achieved this by temporarily reducing the oil flow. This reflects the main advantage of using constrained model-predictive control. The controller returned the discharge-end temperature to its setpoint as soon as the oxygen fell out of constraint. There is a penalty on the feed-end temperature as only one manipulated variable is available for control.

Further improvements to the performance of the controller are being implemented as this paper is being written. Models of the lime mud feed rate are being evaluated to be included as feed-forward variables. Finally, a performance deterioration has been noticed over time as rings formed inside the kiln. Rings are the result of an accumulation of localized cylindrical deposits that are formed as a layer of dust, composed of lime mud and product lime particles, accumulates on the surface of the refractory lining. As a ring grows thicker, the cross-sectional area of the kiln is decreased, restricting the flow of the solids and flue gases through the kiln. This impacts the dynamic behavior of the process, making it vary unpredictably. On-line adaptation could improve the performance of the controller.

CONCLUSION

Consistent lime quality can only be achieved through proper control of the temperature profile along the kiln. Classical control strategy, using PID controllers, has limited success because it does not account for delays and interactions between the operating variables.

A constrained model-predictive control algorithm was implemented on an industrial lime kiln. The control strategy is successful in controlling the temperature profile along the kiln while respecting the constraints in excess oxygen and in the manipulated variables. Under normal operating conditions, the temperatures are controlled within 20°C at the discharge end and within 5°C at the feed end compared to variations of 50°C and 20°C, respectively, with the PID control strategy. The model-predictive strategy is also successful in controlling the temperatures during recurrent upset conditions caused by regular washing of the lime mud filter.

Tighter environmental regulations will soon require continuous monitoring of TRS emissions. The ability to specify constraints (i.e., oxygen) explicitly gives model-predictive control techniques a key advantage for lime kiln control. **TJ**

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