

Control of an industrial lime kiln operating close to maximum capacity

David R. Osmond, Patrick J. C. Tessier, and Martin Savoie

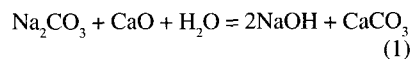
ABSTRACT: Two control strategies have been compared for an industrial lime kiln operating close to maximum capacity. Transfer functions between process inputs (fuel flow rate, air flow rate, and lime mud flow rate) and process outputs (oxygen excess, cold-end gas temperature, and hot-end solids temperature) have been used to present the dynamics of the industrial kiln.

Control Strategy 1 manipulates the fuel flow rate to control the cold-end gas temperature and the combustion airflow rate to control the hot-end bed temperature. Control Strategy 2 uses the combustion airflow rate to control the cold-end gas temperature and the fuel flow rate to control the hot-end bed temperature.

Both strategies use feedback proportional integral (PI) controllers, decouplers, and feedforward loops. Simulations show that Strategy 1 would maintain better product quality than Strategy 2 in the event of periodic fuel actuator saturation resulting from increased production requirements.

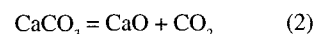
KEYWORDS: Capacity, control systems, lime kilns, models, simulation, temperature control.

The lime kiln is an essential component of the kraft recovery and recausticizing system. The recausticizing plant uses lime, CaO, to generate sodium hydroxide, NaOH, from the sodium carbonate, Na₂CO₃, in the green liquor according to the following reaction.



The Na₂CO₃ is retrieved from the black liquor in the recovery furnace, and the NaOH makes up part of the white liquor that is sent to the digester for pulping the wood chips. It is the function of the rotary lime kiln to recover

CaO from the CaCO₃ produced in the recausticizing plant. This is done by calcining CaCO₃ to form CaO and CO₂ according to the following chemical reaction.



Ideally, the kiln should be able to produce sufficient, high-quality lime to meet the needs of the recausticizing operation while minimizing its energy consumption and total reduced sulfur (TRS) emissions.

As shown in Fig. 1, a lime kiln is essentially a very large direct-contact heat exchanger. Its purpose is to dry the incoming CaCO₃ mud, which is typically at about 30% moisture, and heat it to a high enough temperature for calcination to take place. High-quality lime is very reactive. The reactivity depends upon its CaO content, its particle size distribution, and its porosity. The relationship between lime quality, lime mud characteristics, and kiln operating conditions is not completely understood, although we know that the temperature profile of the kiln plays a significant role.

Heat energy is provided to the kiln through fuel combustion at the hot-end of the kiln. Combustion air also enters the kiln at the hot-end and distributes the resulting heat energy down the length of the kiln. This energy is subsequently transferred to the CaCO₃ bed, which flows down the kiln countercurrently to the flow of the combustion air.

Clearly, lime kilns are multivariable and distributed systems. For any

Osmond is a control system engineer, now at Cariboo Pulp and Paper Co., P.O. Box 7500, Quesnel, BC, Canada V2J-3J6. Tessier is an assistant professor at the University of British Columbia, Department of Chemical Engineering, 2216 Main Mall, Vancouver, BC, Canada V6T 1Z4. Savoie is a research engineer at Noranda Technology Centre, 240 Hymus Blvd., Pointe Claire, PQ, Canada H9R 1G5.

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given feed or production rate, there is an optimal set of operating conditions that provides the best quality lime. It is the purpose of lime kiln control systems to ensure consistent, high-quality lime production by maintaining these operating conditions despite fluctuations in the process inputs. Control systems that accomplish this minimize the extent of process variation, which results in smoother operation of the kiln, lower fuel consumption, lower operating costs, as well as less wear and tear and lower maintenance costs for the kiln.

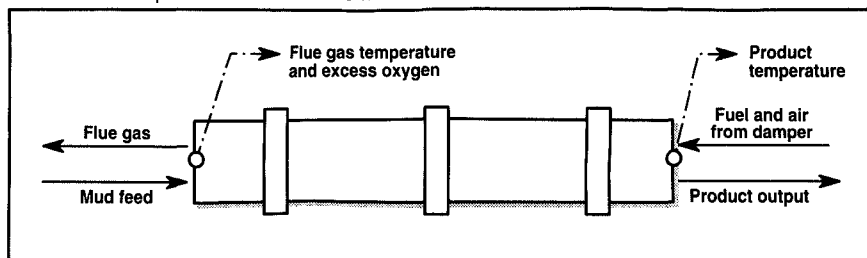
Current control strategies featuring various feedback, feedforward, and dead time compensation techniques have been suggested and/or implemented (1-5). The work presented here uses computer simulations to develop and compare two lime kiln control strategies for the multiple input/multiple output (MIMO) system. Since many industrial kilns are operating close to or beyond their maximum production capacity, emphasis is placed on the ability of the controller to maintain good lime quality under higher-than-production-capacity conditions. The case studied is that of a kiln which is limited in production by its fuel flow actuator.

Lime kiln model

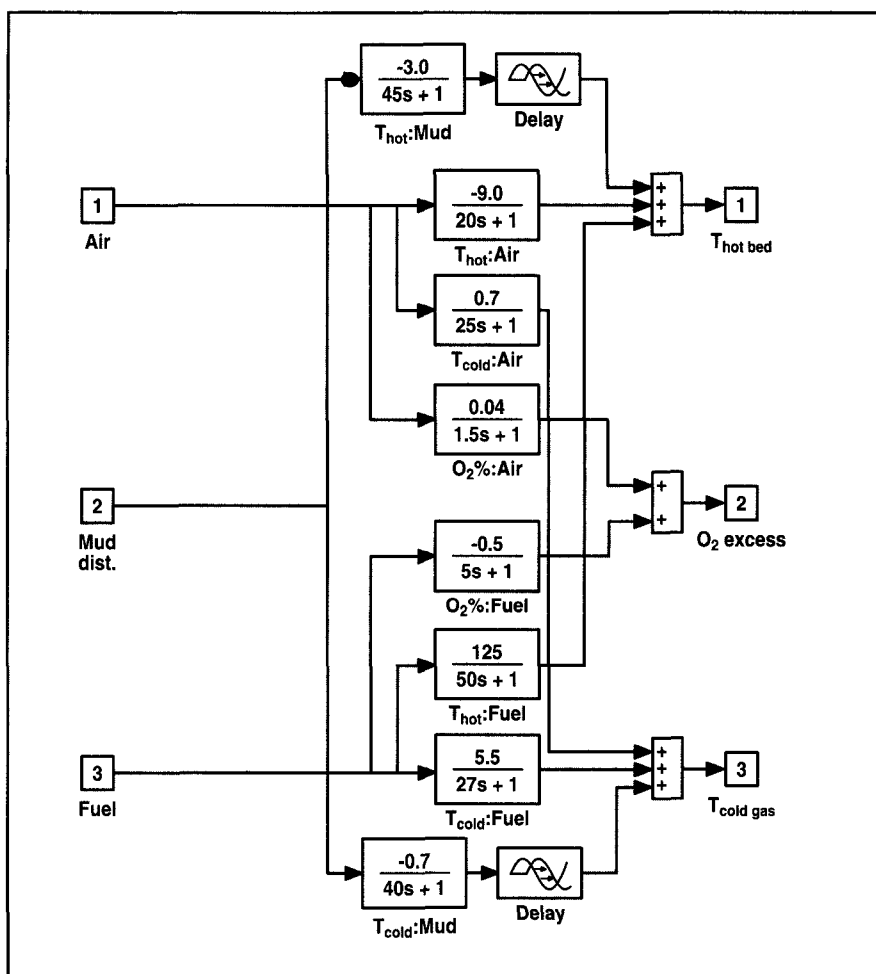
Heat and mass transfer relationships for lime kiln processes are fairly well understood; they are, however, extremely complex (6-8). The development and implementation of a mechanistic model for the purpose of lime kiln control and optimization would, therefore, be extremely difficult and time consuming as partial differential equations are needed to represent the transport phenomena. Instead, transfer functions relating the kiln's inputs and outputs have been used to model the system's dynamic response behavior.

Dynamic process testing of industrial-scale lime kilns must be able to generate useful dynamic response data despite considerable noise levels in the measured parameters and despite the

1. Schematic representation of a lime kiln



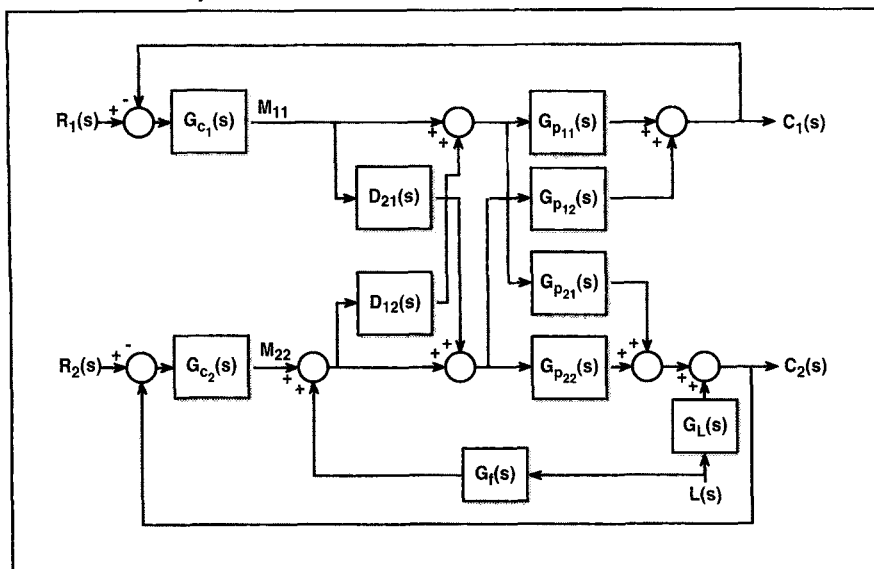
2. Lime kiln model



systems' large time constants and delays. These tests must be done while the kiln is on-line and so should have a minimal impact on its overall production and quality. This process identification was accomplished using bump, or step response, testing. Dynamic response data were collected. First-order transfer functions, with delays where applicable, were generated and provide a good approximation of the

kiln's response curves. The lime kiln model is given in Fig. 2.

The manipulated input variables to the kiln are the combustion air and the fuel. The combustion air is expressed here in percent of its maximum capacity. In the mill, it could be expressed in m³/min and be adjusted using a variable-speed induced-draft fan or dampers in the exhaust gas flue. The fuel is also expressed in percent of its maxi-



imum capacity. In this case, there is only one fuel source, measurable in L/min. Industrial kilns, however, can be equipped to burn several fuels such as natural gas and oil. They can also be used to incinerate waste process by-products. The dynamic model of a kiln with multiple fuel inputs, therefore, would be somewhat more complex since the different fuels would have different heating values. Transfer function relationships are required for each fuel source.

The measured variables are the hot-end bed temperature, cold-end gas temperature, and percent excess oxygen in the flue gas. The lime mud feed rate for the kiln is, in this case, measured as it enters the mud filter. The mud feed rate is expressed in kg/min of equivalent dry solids. This measured value is treated as a disturbance to the system.

With the exception of the impact of lime mud feed variations on the system, all delays were found to be negligible. In other kilns, this may not be the case. The delay found between the measured mud feed variations and cold-end gas temperature changes was 20 min. The residence time of the mud in the kiln (between entering the mud filter and exiting the hot-end of the kiln) was 165 min.

The normal operating condition of

this particular lime kiln converts 285 kg dry solids per minute of lime mud to cooked lime. The hot-end bed temperature is typically 1300°C, and the cold-end gas temperature is typically 220°C. The fuel flow is typically 95% of its capacity while the airflow is 50%. These values are used during the simulation work as the process initial conditions from which the controllers operate in deviation variables.

Note that, with this dynamics identification technique, a lime kiln exhibits highly nonlinear characteristics, and its operating conditions may vary. The model presented here is a linear approximation of the system's dynamic behavior around the kiln's standard operating range. The accuracy of the kiln transfer function responses, and therefore the quality of the control, may decrease as the operating conditions of the kiln vary from these typical operating conditions.

Simulation of lime kiln control strategies

Proper control of a lime kiln requires maintenance of the optimal kiln temperature profile. Since this system is coupled with the fuel and combustion air inputs, and the hot- and cold-end temperatures, it becomes possible to

control either temperature with either input variable. The following simulation work focuses primarily on Control Strategy 1, in which the hot-end bed temperature is controlled by manipulating the combustion airflow rate, while the cold-end gas temperature is controlled using the fuel flow rate (1). An alternative control strategy, Strategy 2, using fuel flow rate to control the hot-end temperature and combustion airflow rate to control the cold-end temperature, also has been simulated for comparison purposes.

Computer simulation is an important tool in control work. It allows testing and evaluating many different control strategies in a relatively short period of time. The simulation's speed and accuracy saves the control engineer and company time, effort, and money in determining which strategy would function best for a given process. Keep in mind, however, that computer-simulated control systems will not usually function as well in practice as they do in simulation. Modeling errors and other differences exist between a real-life system and a computer-simulated one. A computer simulation, however, can reveal trends in the control system, illustrate the relative differences between configurations, and provide initial values for the real-life controller parameters.

Control work included designing and simulating two Lambda, or internal model control (IMC), tuned PI feed-back control loops. Reset feedback integral windup protection was used to prevent windup during actuator saturation. Decouplers were installed to eliminate interactions between the two control loops. Finally, one feedforward controller was used to compensate for the effects of mud feed variations on the cold-end gas temperature.

Figure 3 represents the control system for the kiln that includes feedback and feedforward loops as well as decouplers. The block diagram is the same for both control strategies, but the I/O (input/output) transfer functions differ.

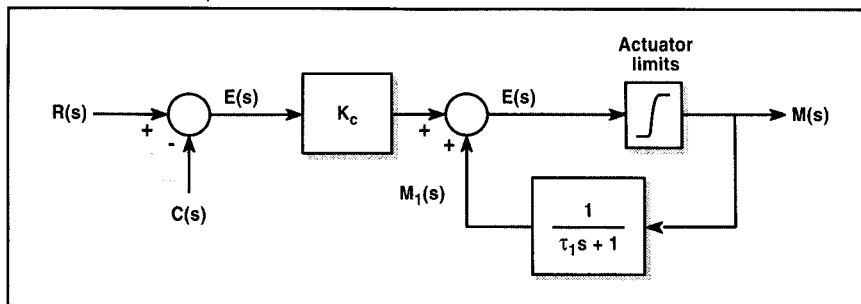
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The most important component in this control strategy is the feedback controller. The Lambda tuning method permits the design of simple PI controllers with significantly smaller closed-loop response times than those of the open-loop time constants of the process. As the closed-loop time constant is reduced, the kiln's response to system changes becomes faster. The system, therefore, will be better maintained at its setpoint values, and the overall production will be more uniform. However, as the closed-loop time constant decreases, the stress placed on the actuators increases.

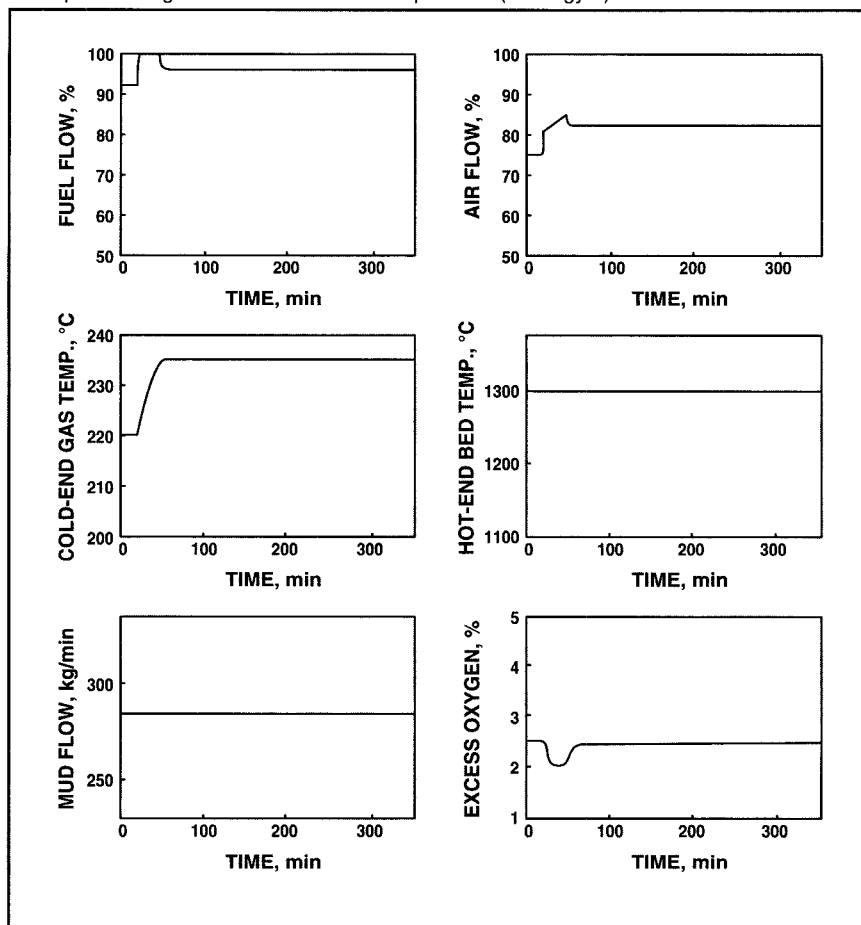
The modeled kiln operates very close to, and quite often beyond, its fuel flow actuator capacity. As a result, the controller quite often requires an actuator setting beyond its range of operation. When this happens, the actuator saturates, and a sustained error exists between the controller's setpoint and the output of the system. The integral term of the PI controller will continue to increase (integrating the error) in an attempt to eliminate this error even though the actuator is incapable of producing a larger output. This windup of the integral term will cause the system to overshoot its setpoint and could introduce some oscillations into the system. Several strategies exist for protecting the controllers from integral windup. Using the velocity form of the PI controller is a good solution. The technique that has been used here is known as the reset feedback implementation (9) and is illustrated in Fig. 4. Integral windup, in an industrial setting, is less of a problem, since anti-windup protection is supplied as a standard feature with most control systems within the configurable control loop.

The design of the Lambda feedback controllers does not take into account the coupled nature of the system. Any action taken by either of the controllers affects the other control loop, resulting in disturbances in the output variables. Decouplers reduce the system fluctuations by eliminating the interactions between the lime kiln's

4. Reset feedback implementation



5. Setpoint change of 15°C in cold-end temperature (Strategy 1)



control loops. The impact of M_{22} on C_1 (Fig. 3) is given by

$$C_1 = M_{22} \left(G_{p12} + D_{12} G_{p11} \right) \quad (3)$$

and the impact of M_{11} on C_2 is given by

$$C_2 = M_{11} \left(G_{p21} + D_{21} G_{p22} \right) \quad (4)$$

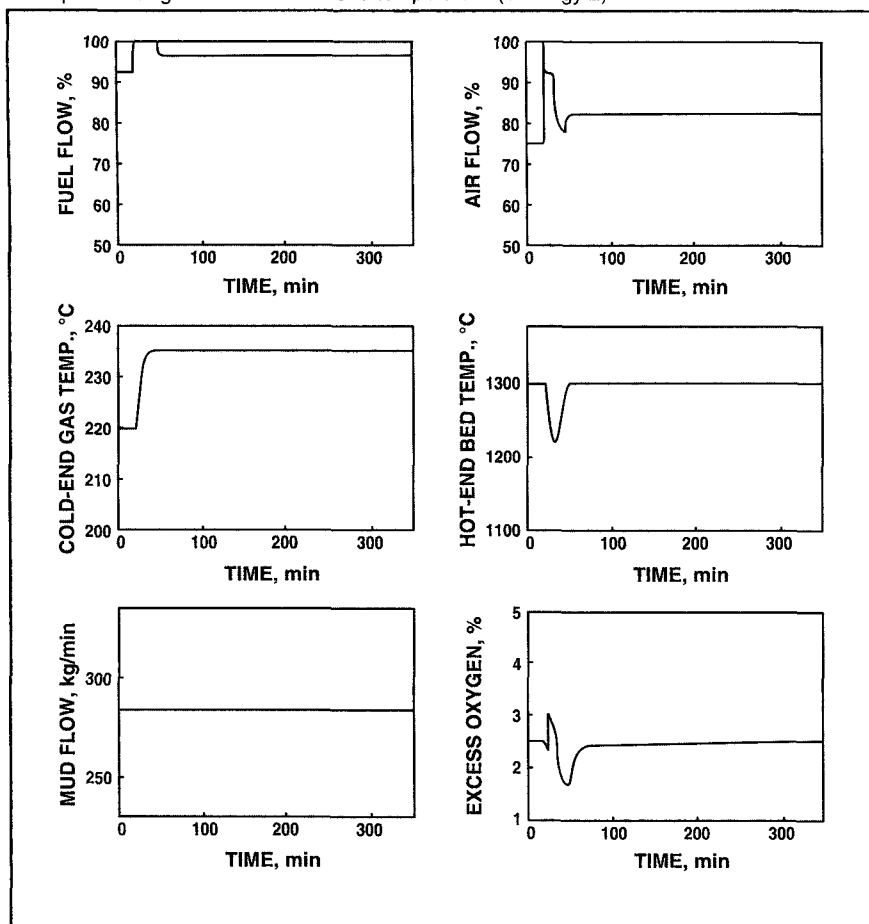
To eliminate the process interaction

we require:

$$D_{12} = -\frac{G_{p12}}{G_{p11}} \quad (5)$$

$$D_{21} = -\frac{G_{p21}}{G_{p22}} \quad (6)$$

6. Setpoint change of 15°C in cold-end temperature (Strategy 2)



These decouplers can be considered as feedforward controllers from the output of one controller to that of the other.

The final aspect of kiln operations examined is the effect of disturbances in the mud flow rate on the system. Variations in mud feed rate occur regularly in industrial lime kilns and can have a substantial impact on the kiln's performance. A feedforward controller was used to compensate for the effects of mud feed rate variations on the cold-end temperature of the kiln.

Referring to Fig. 3, the closed-loop transfer function between L and C_2 is given by

$$\frac{C_2}{L} = \frac{G_L + G_F G_{p_{22}} + G_F G_{12} G_{p_{21}}}{1 + G_{c_2} G_{p_{22}} + G_{c_2} D_{12} G_{p_{21}}} \quad (7)$$

To keep the output constant despite changes in the mud flow rate L , the

following must apply:

$$G_L + G_F G_{p_{22}} + G_F D_{22} G_{p_{21}} = 0 \quad (8)$$

therefore

$$G_F = -\frac{G_L}{G_{p_{22}} + D_{12} G_{p_{21}}} \quad (9)$$

No feedforward control has been implemented to compensate for variations in the hot-end temperature resulting from disturbances in the mud feed rate. The step response tests conducted to identify this interaction were not conclusive due to time and production limitations. As a result, no feedforward control could be reliably and accurately simulated. A transfer function, however, was developed in order to complete the model. This function was based on the inconclusive step response results as well as on previously conducted residence time test-

ing performed by the mill. We believe that the dynamic response of the feed-back-controlled system would be faster than the dynamics of mud feed disturbances on the hot-end temperature. Any resulting disturbance to the hot-end temperature would be small and short-lived.

Results of simulation and comparison between the control strategies

Because of the physical constraints of the kiln, the performances of the two control strategies differ. Figure 5 illustrates one impact of kiln constraints on the overall performance of the system using Control Strategy 1. An increase in the cold-end temperature setpoint of 15°C requires a larger output from the kiln's fuel actuator than is possible. The speed of the kiln's response in this case is therefore limited by the fuel actuator's ability to provide the flow requested by the controller. The result is a system response time of about 30 min rather than the 2.5 min closed-loop response time of the PI controllers. Note that there are no overshoot or system oscillation problems present that could be associated with integral windup.

Control Strategy 2, however, behaves differently when subjected to the same setpoint changes, as shown on Fig. 6. Here the airflow increases in order to achieve the desired cold-end setpoint. The fuel flow rate, however, is limited by its constraints and cannot increase sufficiently to compensate for the changes in the system. The result is a temporary but substantial drop in the hot-end temperature of the kiln.

The mud feed disturbance simulations reveal that an increase in the solids feed rate of 33 kg/min requires a steady-state fuel flow rate of almost its maximum value. Any feed rate increase larger than 33 kg/min (or total dry solids feed rate larger than 318 kg/min) requires a fuel flow rate beyond the value of its constraints. Large increases in mud flow rate from steady

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state, therefore, will result in saturation of the fuel actuator. As a result, the effect on the quality of control for each strategy is significantly different.

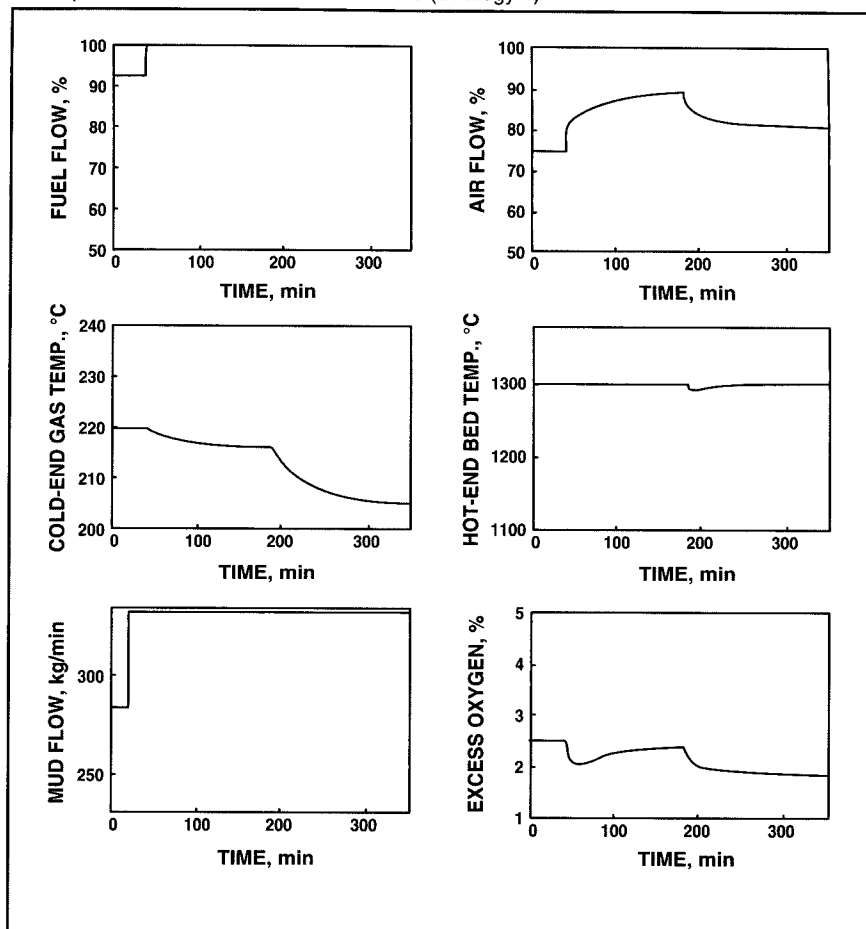
With Control Strategy 1, large increases in the mud flow rate from steady state will result in saturation of the fuel actuator and thus a drop in the kiln's cold-end temperature from its setpoint value, as shown on Fig. 7.

These simulation results suggest that with Strategy 1 the real kiln will be limited by its fuel flow constraints before it has reached its combustion airflow constraints. In the event of a large increase in the mud feed rate, the hot-end temperature setpoint will be maintained through manipulation of the combustion airflow rate. Lime quality is more dependent on the hot-end bed temperature of the kiln than the cold-end gas temperature, and thus product quality will not deteriorate significantly (10). The cold-end temperature setpoint of the kiln will be unattainable due to the limitations of the fuel actuator. For a kiln such as the one modeled—operating close to its maximum capacity—this will be a common occurrence and is a drawback worth serious consideration. The cold-end setpoint could only be reached under these conditions by decreasing the hot-end setpoint. If the cold-end temperature remains low for an extended period, however, kiln operations will eventually suffer, as these conditions can result in ring and ball formation.

With Strategy 2 (Fig. 8), if the fuel actuator saturates, the control system's ability to maintain the hot-end setpoint is lost; the hot-end temperature drops from its setpoint target. The control system, however, is able to maintain the cold-end setpoint. The impact on the system in this case is more significant than the equivalent scenario with Strategy 1.

For a kiln operating near maximum capacity, Strategy 2 would be inappropriate. These kilns often must operate with mud feed rates beyond their production capacity. When this occurs,

7. Response to an increase in mud flow rate (Strategy 1)



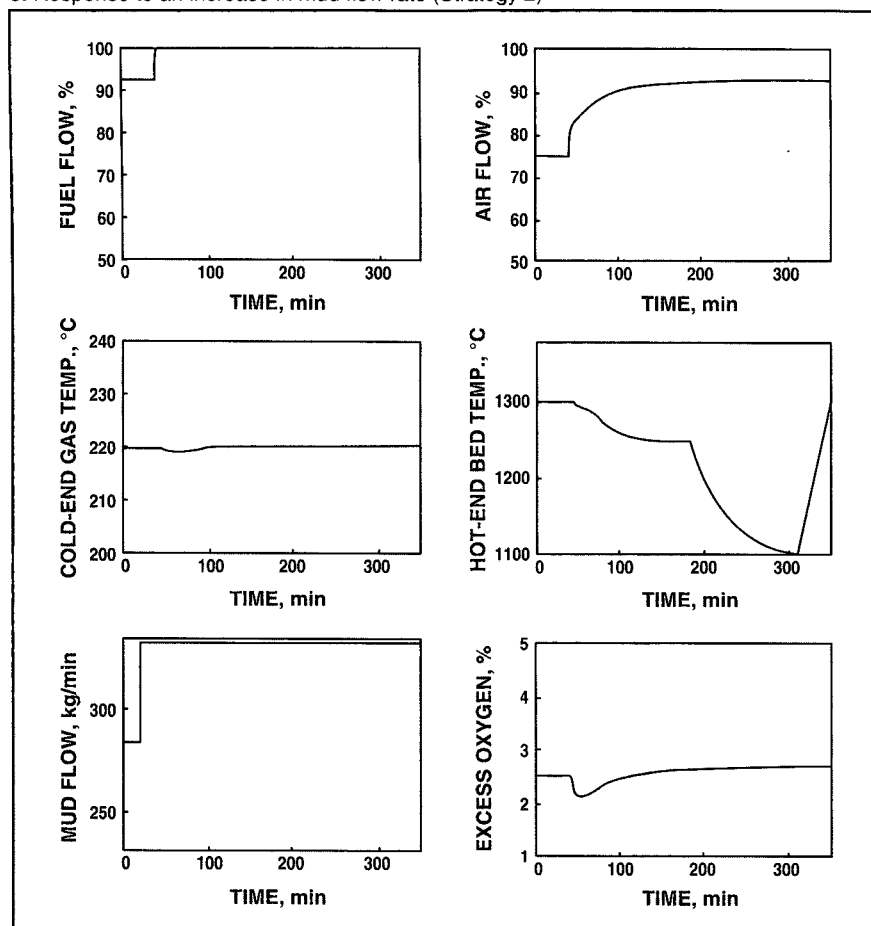
it is much more important to maintain the kiln's hot-end bed temperature than it is to maintain the cold-end gas temperature.

Strategy 1 would maintain better product quality than Strategy 2 in the event of periodic fuel actuator saturation resulting from increased production requirements. Consequently, Strategy 1, which uses the combustion airflow rate to control the hot-end temperature, and the fuel flow rate to control the cold-end temperature in conjunction with feedback control, integral windup protection, decouplers, and feedforward controllers in place, is the better strategy for use on a lime kiln that is limited by its fuel flow.

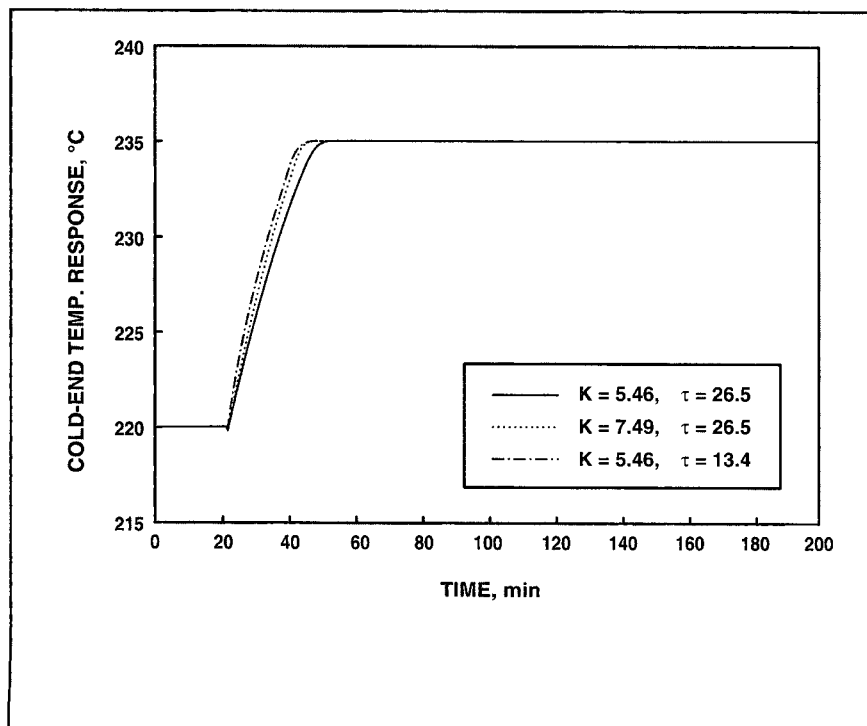
The dynamic responses of the excess oxygen in the system to input parameter changes have been included in the system model and the response of the excess oxygen generated for all

of the simulation trials. The intent was to observe the oxygen response in order to determine whether some type of oxygen controller, possibly in cascade with the combustion airflow controller, should be considered. The suggested excess oxygen minimum and maximum limits are 1.5% and 5.0%, respectively. Below 1.5% excess oxygen, the kiln generates unacceptably high total reduced sulfur (TRS) emissions levels in its flue gas. Above 5.0%, there is too much airflow through the kiln, and considerable energy is lost from the system in the flue gas. None of the simulations carried out for the system with reset feedback, decouplers, and feedforward controllers generated fluctuations in the excess oxygen beyond the suggested oxygen limits. Therefore, no excess oxygen control was attempted on the system, as it would have had no ob-

8. Response to an increase in mud flow rate (Strategy 2)



9. Robustness test for fuel transfer function error



servable effect on the simulation results. However, this will probably not be the case for other kilns, and excess oxygen control may be needed (1).

Sensitivity of Control Strategy 1 to model mismatch

The rotary kiln model used in the previous dynamic simulation and control work is not necessarily an accurate representation of the kiln's dynamic behavior; the dynamic model used may contain some error. The transfer function parameters are the average values determined over several process identification trials. The sensitivity to model mismatch, or robustness, of the control system is tested by changing the parameters of the model's transfer functions while keeping the control system tuning and design the same. A robust controller will be able to maintain good control of the system despite deviations in the system model.

Each of the model gains and time constants was changed according to the corresponding standard deviation of the trial results. The performance of the control system is evaluated for errors in each model parameter. The largest impact on the control system will occur when the transfer function gains are increased and the transfer function time constants are decreased.

The first-order dynamic response of the cold-end gas temperature to changes in the fuel flow rate had a gain of 5.5°C·min/L and a time constant of 27 min. A new model gain and time constant were calculated according to the standard deviation of the bump test trial results. These are shown in Table I. Each change in the model was then simulated to determine the sensitivity of Strategy 1 to errors in these model parameters. The simulation results are shown in Fig. 9.

Similar calculations and simulations were carried out on the rest of the kiln's model transfer function parameters, and the system's performance was observed. As expected, introducing these modeling errors changed the performance of the system. However,

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none of the errors resulted in any significant change in the overall quality of control. The desired steady-state values of the system are reached, and the changed dynamics introduce only small disturbances to the system. The oscillations introduced to the system are only a few degrees in amplitude and short-lived. Also, the system response times are not adversely affected. Changes of this magnitude are negligible when considering the scale and range of industrial rotary lime kiln operations.

Conclusion

The smooth and efficient operation of the kraft mill recovery and recausticizing system is dependent on the smooth operation of each of its components. The rotary lime kiln is an important part of this system and one which benefits greatly from the im-

I. Transfer function between fuel flow and cold-end temperature

	Average value	Standard deviation	New value with modeling error
Process gain (K), °C•min/L	5.5	2.0	7.5
Time constant (τ), min	27	13	14

provement in product quality achieved through the installation of a control system.

This report has investigated the modeling, simulation, and control of a rotary lime kiln. The particular kiln that was modeled operates very close to its maximum fuel flow rate, and thus its maximum capacity. With this kiln, a control system configuration was developed using reset feedback PI controllers, process decouplers, and feedforward controllers. This control configuration, under various simulation conditions, works very well in providing fast system responses while eliminating the oscillation and overshoot problems inherent in a constrained, multivariable system.

The coupled nature of the lime kiln process makes it possible to control the hot-end or the cold-end temperature by manipulating either of the system's two main inputs, the fuel flow rate or the combustion airflow rate into the kiln. The close relationship between product quality and the hot-end temperature makes it imperative that the lime kiln control strategy gives priority to maintaining the hot-end bed temperature within the setpoint range. Control Strategy 1 gives priority to maintaining the hot-end temperature, despite periodic fuel actuator saturation, by manipulating the combustion airflow to control the hot-end temperature and the fuel flow to control the cold-end temperature. This control strategy, in conjunction with reset feedback controllers, decouplers, and feedforward control, is recommended

as a means of providing good control to this rotary lime kiln. The control quality remains good despite the most extreme cases of model mismatch.

Similarly, one can expect that a kiln limited by its combustion airflow capacity would benefit most from the implementation of Control Strategy 2. The higher fuel flow capacity could then be best used in maintaining the hot-end bed temperature. **□**

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