

Performance evaluation of two simple causticizing control systems

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THE CAUSTICIZING PROCESS PLAYS a crucial role in the recovery of inorganic chemicals from the kraft pulping process. Its purpose is to produce high-quality, low-variation white liquor for use in the mill's digesters. Typically, a white-liquor active alkali (AA) of 6.2–6.4 lb/ft³ (as Na₂O) and a causticity around 80% are desired. Low-quality white liquor reduces process efficiency throughout the entire mill operation, so it is vital to tightly control the quality of the white liquor. Another important control consideration is safety, since slakers are often operated at temperatures only a few degrees below the boil-over temperature.

In the last few years, the pulp and paper industry has focused greater attention on the causticizing process after years of neglect. The development of advanced sensor equipment—toroidal conductivity probes, nuclear density meters, and automatic titrators—has revitalized the industry's efforts to achieve tighter causticizer control. However, there are no studies comparing the performance of the typical causticizing control schemes employed by the industry.

In this paper, a physically based dynamic model of the causticizing process, developed by Swanda *et al.* (1), is used to simulate the closed-loop responses of two control systems. The model contains mass and energy balances for a slaker/classifier followed by three causticizers. Parameters for the physically based dy-

namic model were tuned using industrial open-loop response data from a dynamic experiment and then validated using industrial data obtained from a second dynamic experiment and during steady-state operation. The modeled results were in excellent agreement with all collected mill data. The model has been used on an industrial scale to examine process dynamics and can be used to evaluate and improve causticizing process-control systems.

EXISTING CONTROL SYSTEMS

In today's kraft pulp mills, the process control systems vary widely in complexity. Some mills use only a few proportional-integral (PI) controllers, with operators adjusting the lime addition rate. Other mills use advanced control packages such as the Kemotron CCS 2400, which includes a microprocessor and numerous conductivity measurements (2).

In the simplest control scheme, the ratio of lime to green liquor is normally specified by an operator, who relies on the temperature increase across the slaker, laboratory analysis of the white liquor reported every several hours, and experience. Because laboratory analysis is typically available only once per shift, the operator is not able to follow short-term variations in green-liquor composition and lime quality, which often results in inappropriate control actions. The ratio of lime to green liquor is one of the most important control variables, and inappropriate control actions can produce large

ABSTRACT

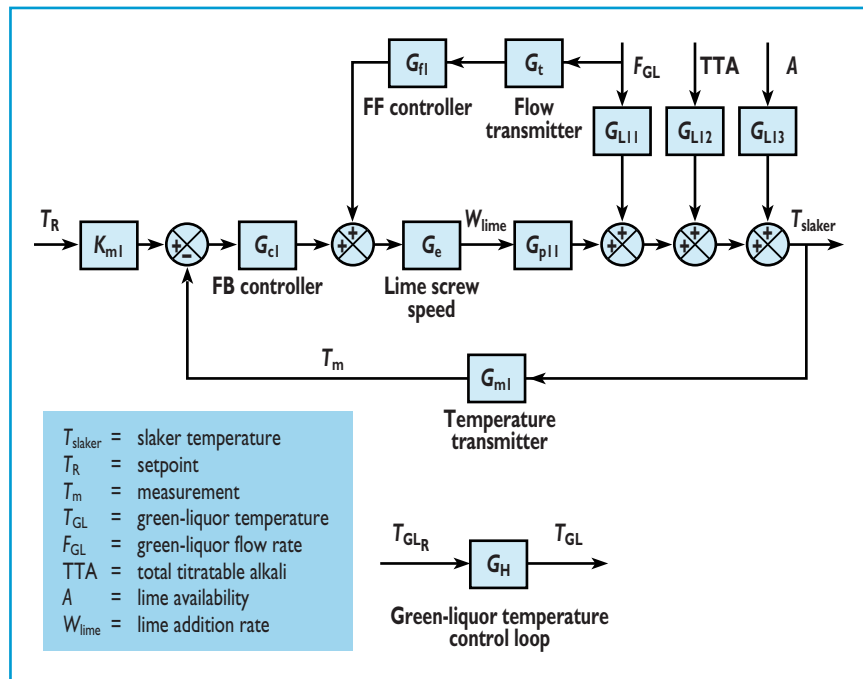
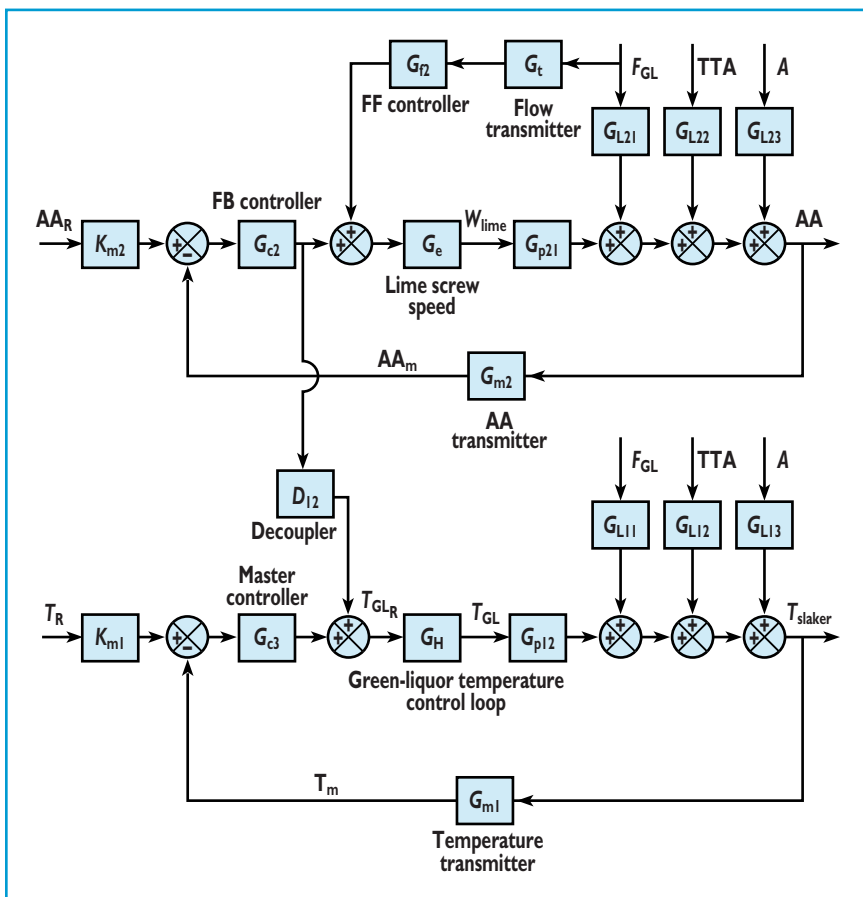
The dynamic performance of two causticizing control systems—"ΔT control" (a system based on control of slaker temperature) and "inferred AA control" (a system based on an inferred measurement of active alkali (AA) in the first causticizer)—was evaluated using the physically based model developed by Swanda *et al.* [TAPPI J. 80(12): 123(1997)]. The performance of each system was assessed by comparing its ability to maintain control in response to two common process disturbances: an upward drift in green-liquor total titratable alkali (TTA) and a drop in lime availability for the slaking reaction. Slaker temperature, first-causticizer AA, final AA for the product white-liquor, and the initial and final percent white-liquor causticity were considered in the evaluation. The inferred-AA control system outperformed the ΔT control system by maintaining first-causticizer and white-liquor AA values closer to their targets. Peak errors for the ΔT control system were from 1.6 to 4 times larger, and its settling times were slightly longer.

Application:

The results of this study can be used in the design or redesign of a control system for the causticizing process.

variations in AA and causticity for the white-liquor product.

To improve control and reduce operator intervention, many pulp mills control the temperature difference between the slaker inlet stream and the slaker reactor vessel ("ΔT control") by adjusting the lime addition rate via a PI controller or a microprocessor-based algorithm (3). In effect, the addition of lime is controlled to a setpoint, since the slaking heat of reaction is more than one order of magnitude greater than both

1. Block diagram for the ΔT control system

2. Block diagram for the AA control system

the causticizing heat of reaction and the heat loss to ambient. However, ΔT control strategies cannot correct for changes in green-liquor composition, since compositional changes have an insignificant effect on liquor temperature. An improved control strategy that utilizes an on-line AA sensor would be more effective at controlling white-liquor quality, since it would detect the effect of changes in both green-liquor composition and lime reactivity on AA.

Because of the limitations of ΔT control strategies, feedback control of lime addition—based on direct or an inferred measurement of liquor species—has been implemented. Automatic titrators are commercially available to measure liquor properties, but these devices are expensive, maintenance intensive, and prone to failure in the harsh chemical environment. Moreover, wet chemical titrators and gas chromatographs both require sample conditioning to determine sodium carbonate concentration in a multicomponent mixture. This requirement increases the time delay between sampling and reporting. In addition, pluggage of the sample line can be a major maintenance problem. An alternative measurement device is a toroidal conductivity probe that can be used to infer AA, EA (effective alkali), and causticity in the first causticizer (4). Typically, the measurement is used as a feedback signal for PI control of lime screw speed. A study by Lynn (4) concluded that “conductivity alone can be used as an adequate measure of causticity for continuous feedback control of lime to the slaker, for typical green liquor TTA (total titratable alkali) variability.” Also, Green and Hough (5) reported that “mills currently using the conductivity control technique have reported excellent results, with the ability to continuously operate close to equilibrium conditions without overliming.”

One of the most complex and advanced conductivity control techniques is marketed by Kemotron (6). Their control system uses the green-liquor conductivity and density for feedforward control; the weight of lime and conductivity in the first and last causticizers for feedback control; and a microcomputer to make the necessary calculations (7). However, some kraft mills are reluctant to purchase causticizing control packages because of maintenance concerns and a desire to use a DCS-based (distributed control system) control algorithm instead of a packaged proprietary control algorithm. It is easier for plant operating personnel to retune controllers or modify DCS-based control algorithms than it is to modify a proprietary algorithm.

DESCRIPTION OF THE SIMULATED CONTROL SYSTEMS

One of the evaluated control systems, referred to as ΔT control, is used at the Weyerhaeuser test mill and at two of their other mills. This system controls the temperature difference between the green liquor and the slaker. **Figure 1** is a block diagram of the ΔT control system. The blocks in the diagram represent the dynamic relationship between the input and output of each block. The temperature difference is controlled by holding the green-liquor temperature constant via a PI feedback controller (not shown) and by controlling the slaker bowl liquor temperature via a PI feedback (FB) controller and a feedforward (FF) controller. The two manipulated variables are the lime addition rate, W_{lime} , and the steam flow rate to the green-liquor heater. Some mills have the dual capability of heating and cooling green liquor, in which case there is a third manipulated variable, the coolant flow rate. As a simplification, the closed-loop behavior of the green-liquor temperature control loop was modeled using a first-order transfer

function with a 5-min time constant. The transfer function is represented by G_H in Fig. 1, where T_{GLR} is the green-liquor temperature setpoint. The G_H model can represent either a heater or a cooler. The lime screw dynamics are negligible, so G_c is set equal to one, which means that the controller output directly determines the lime addition rate.

Swanda *et al.* (1) reported that slaker and first-causticizer temperature sensors can severely scale, resulting in large measurement lags. The measurement lags were modeled using the following transfer function.

$$G_{ml}(s) = \frac{\exp(-\theta s)}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (1)$$

where

s = Laplace transform variable

τ_1, τ_2 = time constants

θ = delay time (or dead time)

For the Weyerhaeuser test mill, the model parameters were determined to be $\tau_1 = 42$, $\tau_2 = 16$, and $\theta = 7$ min. These values were used in all simulations that included G_{ml} , unless noted otherwise. For a scale-free sensor, the measurement lag is negligible, i.e., τ_1 , τ_2 , and θ are approximately zero.

Figure 2 is a block diagram of the other control system that was considered in this study, the "inferred AA" control system. This control system infers the AA value in the first causticizer using an *in situ* conductivity sensor. The inferred AA measurement is controlled at a setpoint (AA_R) by using a PI feedback controller to manipulate the lime addition rate. In addition, a feedforward controller compensates for changes in the total green-liquor flow rate. The slaker temperature is controlled by using a PI feedback controller to manipulate the green-liquor temperature setpoint. Similar to the ΔT control system, the green-liquor temperature is controlled using a heat exchanger or

cooler. The dynamics of the conductivity (AA) measurement are assumed to be negligible, and the inferred AA measurement is assumed to be accurate.

The AA control loop interacts with the slaker temperature control loop, causing undesirable slaker temperature oscillations during upset conditions. A single decoupler controller, D_{12} , was used to eliminate these interactions. The decoupler adjusts the green-liquor temperature to compensate for the known variation in the lime addition rate. Typically, two decouplers are used to eliminate the undesirable interactions between two control loops (8). However, for this process, green-liquor temperature changes of several degrees have no significant effect on first-causticizer AA, so a second decoupler is not required.

The success of the AA control system depends on accurate measurement of first-causticizer AA. Toroidal conductivity probes have been successfully used to measure liquor AA. Paprican developed a model relating liquor AA and TTA to conductivity (9). Also, Lynn (4) has used toroidal conductivity probes to indirectly measure AA, EA, and causticity in the first causticizer. To prevent drifts in the conductivity measurement due to scaling, the sensor should be cleaned weekly or biweekly.

To simplify the process simulations, no measurement or process noise was included. This is consistent with collected mill data, which showed that there was no significant noise in the on-line measurements and no high-frequency variations in the green-liquor temperature, composition, and flow rate. However, there are possible high-frequency, randomly occurring variations in lime addition rate because of the random packing of the lime in the lime screw. This disturbance source was assumed to be negligible.

Total titratable alkali (TTA)	$[\text{NaOH}] + [\text{Na}_2\text{CO}_3] + [\text{Na}_2\text{S}] + 1/2[\text{Na}_2\text{SO}_3]$
Active alkali (AA)	$[\text{NaOH}] + [\text{Na}_2\text{S}]$
Sulfidity (S)	$100[\text{Na}_2\text{S}] / \text{TTA}$
Causticity (C), %	$100[\text{NaOH}] / \{[\text{NaOH}] + [\text{Na}_2\text{CO}_3]\}$
Lime availability (A), %	Percentage of CaO

* All concentrations are in terms of equivalent Na_2O .

I. Terms characterizing green and white liquors*

Process variable	Value
Green liquor	
TTA, lb/ft ³ (as Na_2O)	7.2
$[\text{Na}_2\text{CO}_3]$, lb/ft ³ (as Na_2O)	4.28
Sulfidity, % (based on TTA)	28.0
Temperature, °F	187
Lime	
Lime addition rate, lb/min	333.7
Lime availability, %	87.8

II. Green-liquor and lime characteristics for all simulations

PROCESS CONDITIONS

A physical model of the causticizing process was used to evaluate the performance of the ΔT control system and the AA control system. Performance was evaluated based on each system's ability to restore control during two common process disturbances: an upward drift in TTA and a gradual reduction in the amount of lime available for reaction. The closed-loop responses for the slaker temperature, the first-causticizer AA, and the white-liquor AA were compared for each control system. In addition, open-loop responses for these same disturbances and process variables were generated and compared with the closed-loop responses.

Process variable	Model
Slaker	
AA, lb/ft ³ (as Na_2O)	5.30
Temperature, °F	216
Classifier AA, lb/ft ³ (as Na_2O)	5.46
First causticizer	
AA, lb/ft ³ (as Na_2O)	5.87
Temperature, °F	208
White-liquor AA, lb/ft ³ (as Na_2O)	6.23

III. Steady-state conditions for the green-liquor and lime characteristics listed in Table I

Steady-state conditions

Table I summarizes the terms used to characterize green and white liquors. The green liquor and the lime characteristics used during all simulations are shown in Table II. These characteristics are typical of the Weyerhaeuser test mill and of other mills. Table III shows the resulting AA for the slaker, the classifier, the first causticizer, and the white liquor and the temperatures for the slaker and the first causticizer. The resulting steady-state conditions are similar to those of the data used to tune and validate the model. The slaker temperature and first-causticizer AA values in Table III were used as setpoints for all simula-

tions. Also, the white-liquor AA value in Table III represents the target value. The control systems were judged on how effectively they maintained the setpoint and target values.

Process disturbances

The two simulated process disturbances were as follows:

1. TTA disturbance—a 0.5-lb/ft³ (as Na_2O) increase in green-liquor TTA ramped over a 6-hour period. The percent Na_2CO_3 , NaOH, and Na_2S of TTA was held fixed.
2. Lime-availability disturbance—a 7% decrease in lime availability ramped over a 3-hour period.

TTA disturbances can result when the dilution of smelt from the recovery boiler is poorly controlled. Lime-availability disturbances typically occur when lime feedstocks are changed or when the lime kiln is poorly controlled.

Controller tuning

The direct synthesis method was used to tune the PI controllers G_{c1} (ΔT system, Fig. 1) and G_{c2} and G_{c3} (inferred-AA system, Fig. 2) (8). This method typically gives an overdamped response for a setpoint step change. To obtain PI controller settings using the direct synthesis method, a first-order plus time-delay transfer function is required. Table IV shows the first-order plus time-delay transfer-function model parameters used to determine controller settings. The model parameters were determined from the open-loop step responses of the physically based model. Models G_{p11} , G_{m1} , G_{p21} , G_{m2} , and $G_{H,p12}$, G_{m1} were used to calculate

Model parameter	ΔT		INFERRED AA		
	G_{p11}	$G_{p11}G_{m1}$	$G_{p21}G_{m2}$	$G_{H,p12}$	$G_{H,p12}G_{m1}$
K_{OL}	0.0876 $\frac{^\circ\text{F}}{\text{lb/min}}$	0.0876 $\frac{^\circ\text{F}}{\text{lb/min}}$	0.00475 $\frac{\text{lb/ft}^3}{\text{lb/min}}$	0.986	0.986
τ , min	17.3	48.7	35.4	23.9	51.7
θ , min	9.3	36.7	27.8	13.1	41.5

IV. Transfer-function model parameters from open-loop responses

	CONTROLLER		
	G_{c1}	G_{c2}	G_{c3}
K_c	7.58 $\frac{\text{lb/min}}{^\circ\text{F}}$	160 $\frac{\text{lb/min}}{\text{lb/ft}^3}$	0.631
τ_i , min	48.7	35.4	51.7

V. PI controller settings for G_{c1} , G_{c2} , and G_{c3}

controller settings for G_{c1} , G_{c2} , and G_{c3} , respectively. Tuning parameter τ_c (the closed-loop time constant) was set equal to the dead time, which was approximately 80% of the process time constant for models $G_{p11}G_{m1}$, $G_{p21}G_{m2}$, and $G_HG_{p12}G_{m1}$. This τ_c value was chosen so that the closed-loop responses were fast and smooth, with less than 5% setpoint overshoot. Table V shows the resulting controller gains K_c and reset times τ_I .

Design of the decoupler controller also requires two dynamic models: G_{p11} and G_HG_{p12} . The goal of the decoupler—to cancel the effect of changes in lime addition rate on slaker temperature—is accomplished by adjusting green-liquor temperature. This cancellation occurs if

$$D_{12}G_HG_{p12} + G_{p11} = 0 \quad (2)$$

Solving for D_{12} gives an expression for the ideal decoupler

$$D_{12} = -\frac{G_{p11}}{G_HG_{p12}} \quad (3)$$

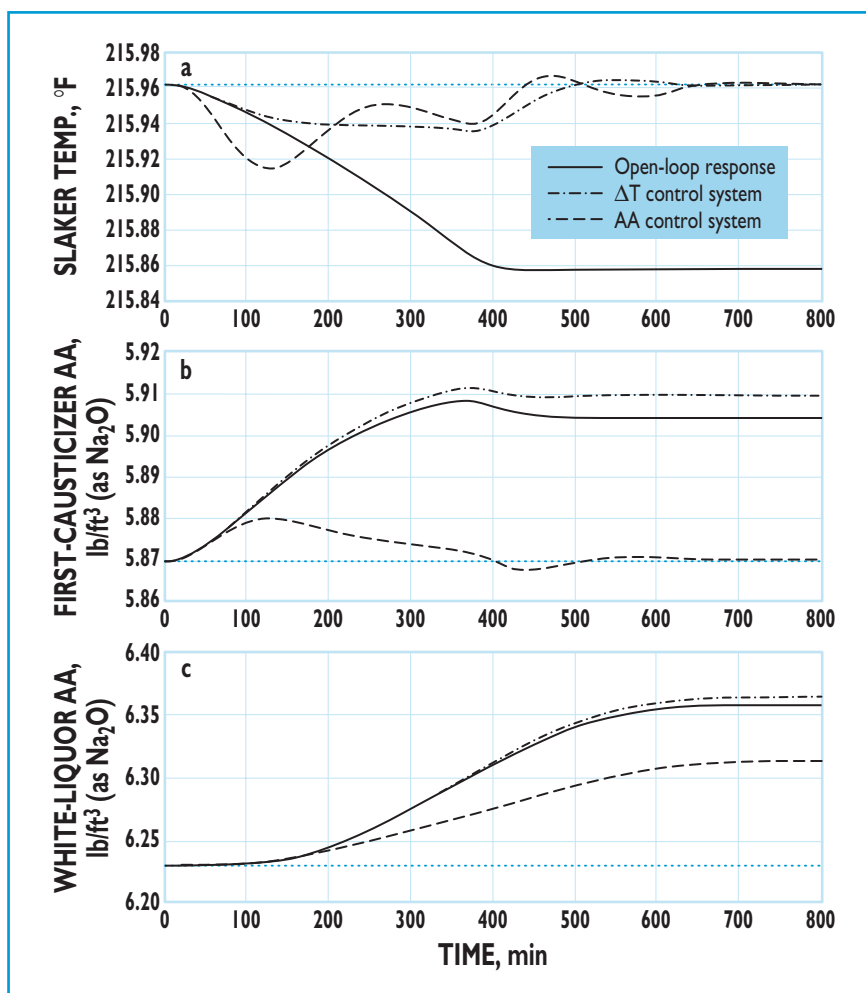
Substituting the G_{p11} and G_HG_{p12} listed in Table IV into Eq. 3 gives the ideal decoupler

$$D_{12} = -0.0883 \frac{23.9s + 1}{17.3s + 1} \exp(3.8s) \quad (4)$$

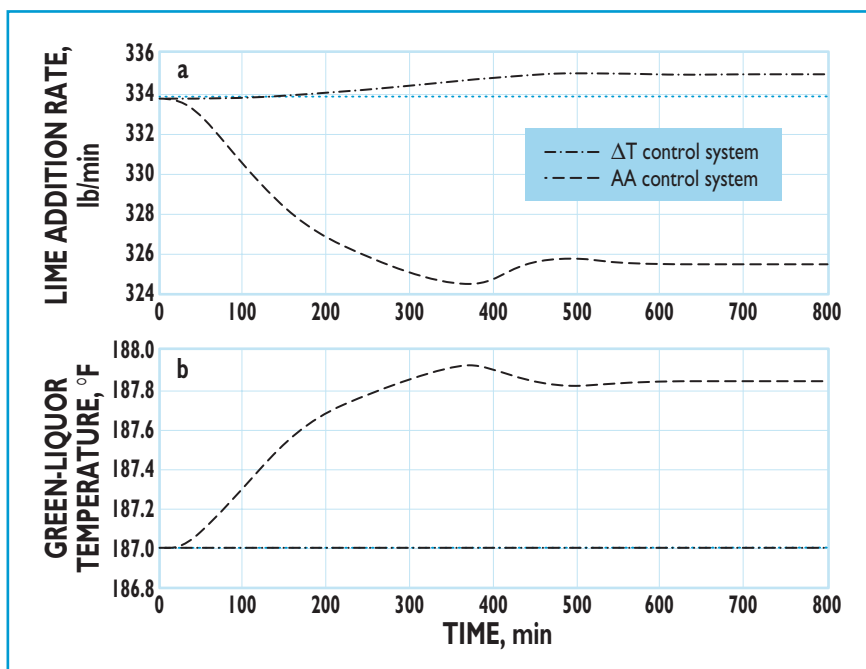
The decoupler is physically unrealizable because of the prediction term $\exp(3.8s)$. However, because the prediction term is relatively small and the time constants in the numerator and denominator of Eq. 4 approximately cancel each other, the ideal decoupler can be estimated by a gain, i.e., $D_{12} = -0.0883^\circ\text{F}/(\text{lb}/\text{min})$. Simulation results are reported for cases with the decoupler implemented and with no decoupler implemented.

SIMULATION RESULTS

The closed-loop responses for slaker temperature, first-causticizer AA, and white-liquor AA were simulated for



3. Slaker temperature, first-causticizer AA, and white-liquor AA closed-loop and open-loop responses during the TTA disturbance



4. Lime addition rate and green-liquor temperature (manipulated variables) during the TTA disturbance

	Settling time, min	Peak error
Slaker temperature		
Open loop	N.A. ^a	-0.103°F
ΔT control system	463	-0.024°F
AA control system	595	-0.045°F
First-causticizer AA		
Open loop	N.A. ^a	0.0382 lb/ft ³ ^b
ΔT control system	...	0.0410 lb/ft ³ ^b
AA control system	473	0.0097 lb/ft ³ ^b
White-liquor AA		
Open loop	N.A. ^a	0.127 lb/ft ³ ^b
ΔT control system	...	0.133 lb/ft ³ ^b
AA control system	...	0.083 lb/ft ³ ^b

^a Not applicable
^b Expressed in terms of equivalent Na₂O
^c Steady-state offset was greater than the settling band width.

VI. Settling times and peak errors for the TTA disturbance

the two control systems. In addition, the closed-loop responses for the manipulated variables—lime addition rate and green-liquor temperature setpoint—were determined. Performance of the control system was judged using settling time and the peak error. In this paper, settling time is defined as the time required for the controlled variable to return inside a band whose width is equal to $\pm 5\%$ of the open-loop response steady-state deviation. Peak error is defined as the largest difference between the setpoint and the controlled variable.

TTA disturbance

The performance of the two control systems was evaluated by tracking their response to a 0.5-lb/ft³ (as Na₂O) increase in green-liquor TTA ramped over a 6-hour period. The percent Na₂CO₃, NaOH, and Na₂S of TTA was held fixed. **Figure 3** compares the closed-loop and open-loop responses of the controlled variables. The closed-loop response of the manipulated variables are shown in **Fig. 4**. The settling time and peak error values are reported in **Table VI**.

The open-loop (no control) response illustrates that the TTA disturbance had almost no effect on slaker temperature, which decreased by

only 0.10°F, as seen in **Fig. 3a**. Such a small change would not be measurable given measurement noise and instrument sensitivity. The reason for such a small change is that slaker temperature is predominately a function of green-liquor temperature and lime addition rate. The slaking heat of reaction is -450 Btu/lb CaO, while the causticizing heat of reaction is -28.6 Btu/lb Na₂O, more than one order of magnitude less. In addition, the dissolved chemical species are too dilute to significantly affect slaker temperature when their feed concentrations change.

The open-loop (no control) response also shows that the TTA disturbance did cause the first-causticizer AA and white-liquor AA to increase by 0.038 and 0.127 lb/ft³ (as Na₂O), as seen in **Figs. 3b** and **3c**, respectively. These results occurred mainly because the green-liquor concentrations of NaOH and Na₂S increased by 0.063 and 0.140 lb/ft³ (as Na₂O), respectively. It took approximately 450 min for first-causticizer AA to increase to its new steady-state value, while it took white-liquor AA approximately 700 min. This may seem long, but the TTA disturbance is ramped up over a 360-min period, and each causticizer has a holdup time of 55 min.

For the AA control system, the first-causticizer AA value promptly settled within 473 min, and the peak error was only 0.0097 lb/ft³ (as Na₂O). In contrast, for the ΔT control system, the first-causticizer AA value did not return to its setpoint, and the peak error was 0.0410 lb/ft³ (as Na₂O), which is greater than the open-loop peak error of 0.0382 lb/ft³ (as Na₂O). The AA control system maintained first-causticizer AA at setpoint by reducing the lime addition rate, as seen in **Fig. 4a**. Because the lime addition rate was reduced, the green-liquor temperature was increased to bring the slaker temperature back to setpoint, as seen in **Fig.**

4b. The ΔT control system slightly increased the lime addition rate because of the small decrease in slaker temperature. With more lime available, more sodium carbonate reacted than in the open-loop case, resulting in a larger increase in first-causticizer AA.

Both control systems failed to return white-liquor AA to its target value. **Figure 3c** shows that the steady-state target offset for the AA control system was 0.083 lb/ft³ as (Na₂O). For the ΔT control system, the steady-state target offset was 0.127 lb/ft³ as (Na₂O), which is greater than the open-loop offset. Offset is expected for the ΔT control system, given that the lime addition rate was not significantly adjusted. However, the AA control system did lower the lime addition rate to force the first-causticizer AA back to setpoint. This result shows that if it is desired to force the white-liquor AA value back to its target value, then the lime addition rate would need to be reduced further. This could be achieved by reducing the first-causticizer AA setpoint through operator intervention or through the addition of a white-liquor AA control loop. This loop could infer white-liquor AA and calculate a first-causticizer AA setpoint, i.e., cascade control.

Besides maintaining a target white-liquor AA value, it is important to maintain a high white-liquor causticity value. The TTA disturbance caused the concentration of sodium carbonate in green liquor to rise. In order to maintain the causticity value, the lime addition rate would have to be increased to convert the additional sodium carbonate in the feed. However, the ΔT control system did not significantly increase the lime addition rate, and the AA control system reduced the lime addition rate to drive first-causticizer AA back to setpoint. Therefore, the causticity value decreased from 79.5% to 74.2% for the ΔT control system and to

	Settling time, min	Peak error
Slaker temperature		
Open loop	N.A. ^a	-2.32°F
ΔT control system	293	-1.10°F
AA control system	320	-1.20°F
First-causticizer AA		
Open loop	N.A. ^a	-0.139 lb/ft ³ b
ΔT control system	343	-0.061 lb/ft ³ b
AA control system	292	-0.039 lb/ft ³ b
White-liquor AA		
Open loop	N.A. ^a	-0.191 lb/ft ³ b
ΔT control system	505	-0.061 lb/ft ³ b
AA control system	438	-0.037 lb/ft ³ b

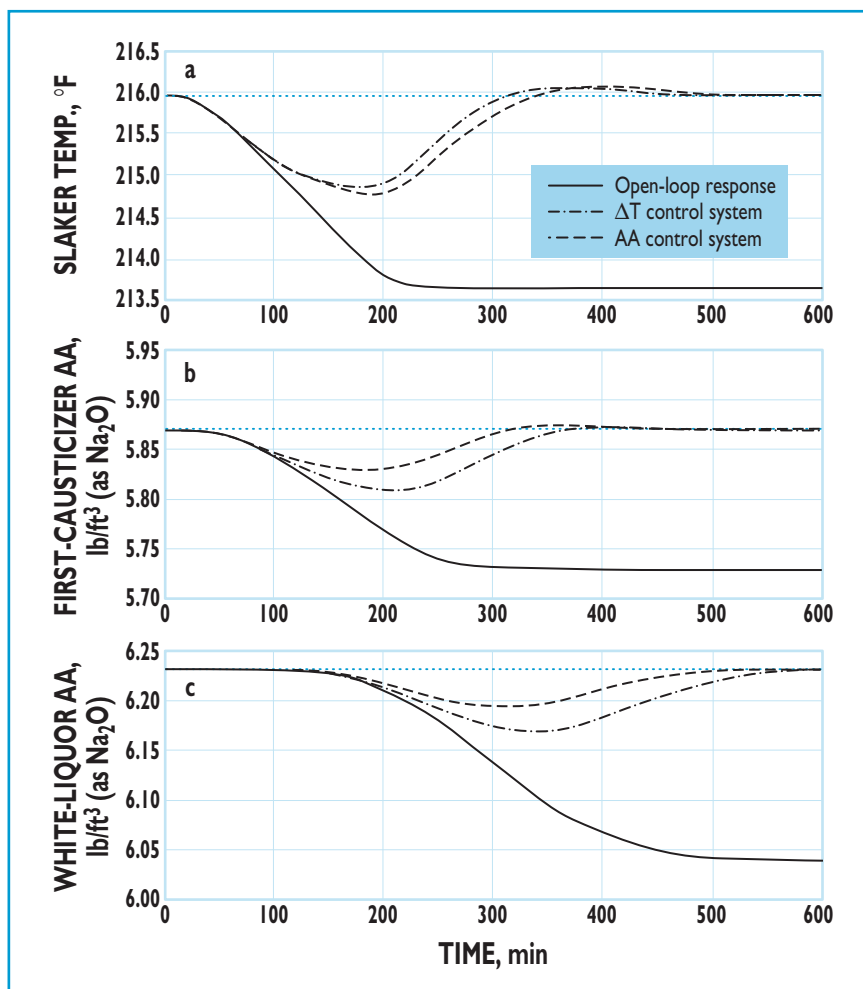
^a Not applicable
^b Expressed in terms of equivalent Na₂O

VII. Settling times and peak errors for the lime-availability disturbance

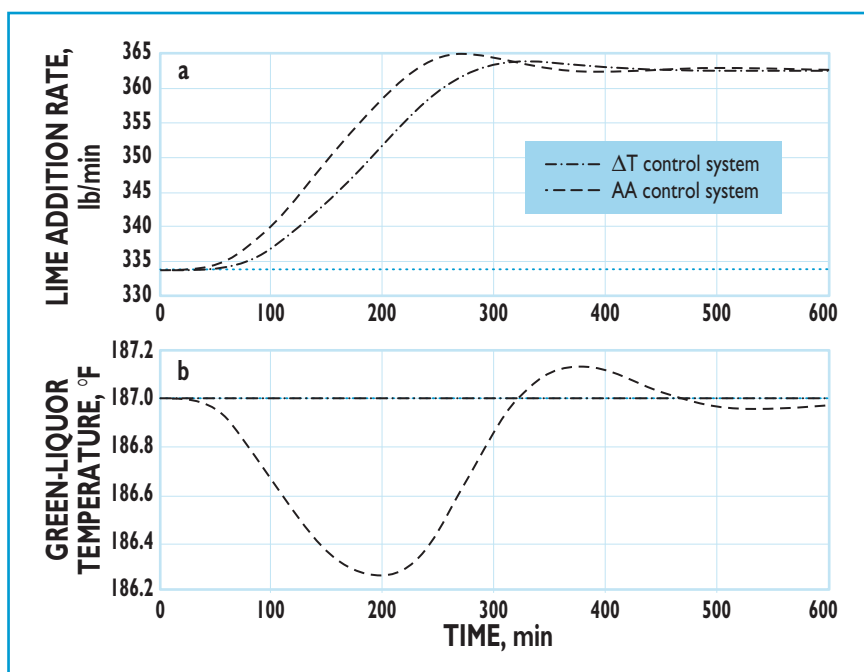
73.3% for the AA control system. Thus both control systems did a poor job at maintaining a high causticity value. This results in a higher sodium carbonate dead load in the white liquor, which will adversely affect the operations of the chemical recovery plant, increasing the heat duties in the digesters and evaporators while reducing the effective capacity of the recovery boiler. However, if the lime addition had been increased, white-liquor AA would have increased significantly, which is also undesirable, since variation in white-liquor AA reduces digester efficiency. Thus, it is not possible to control both AA and causticity by solely manipulating the lime addition rate. However, both variables can be controlled by manipulating the green-liquor TTA and the lime addition rate. Thus it is important to tightly control green-liquor TTA at a desired value.

Lime-availability disturbance

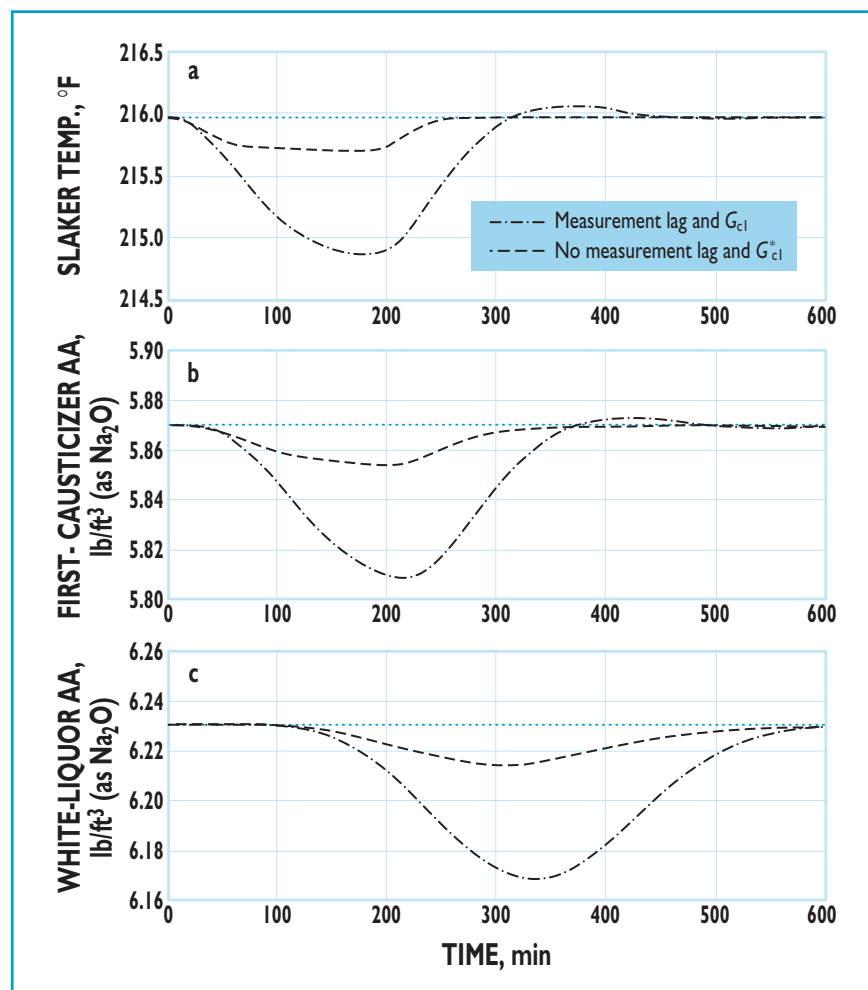
The performance of the two control systems also was evaluated by tracking their response to a 7% decrease in lime availability ramped over a 3-hour period. Figure 5 compares the closed-loop and open-loop responses of the controlled variables. The closed-loop response of the manipulated variables are shown in Fig. 6. The settling time and peak error values are reported in Table VII.



5. Slaker temperature, first-causticizer AA, and white-liquor AA closed-loop and open-loop responses during the lime-availability disturbance



6. Lime addition rate and green-liquor temperature (manipulated variables) during the lime-availability disturbance



7. Comparison of the closed-loop responses of the ΔT control system during the lime-availability disturbance with and without a time lag in measurement of slaker temperature

The open-loop (no control) response in Fig. 5a shows that the lime-availability disturbance caused a decrease in slaker temperature of 2.32°F. This occurred because the disturbance reduced the available CaO in the lime for slaking. The shape of the open-loop response is ramplike because the lime-availability disturbance ramped down over a 180-min period. The response reached its second steady state approximately 220 min after the disturbance began.

The open-loop responses also show that the disturbance led to decreases in first-causticizer AA of 0.139 lb/ft³ (as Na₂O) and white-liquor AA of 0.191 lb/ft³ (as Na₂O), as seen in Figs. 5b and 5c, respectively. Because the disturbance reduced the

available CaO in the lime for slaking, less Ca(OH)₂ was present to react with Na₂CO₃ to form NaOH, which explains the decrease in liquor AA. The shapes of the open-loop responses were less ramplike and took longer to reach new steady states than the slaker temperature open-loop response because of the significant holdup in each causticizer.

Both control systems were able to return the slaker temperature and first-causticizer AA to their setpoints, and the white-liquor AA to its target value, within 600 min. Figure 6 shows that the lime addition rate was increased to compensate for the lower lime availability and that the AA control system temporarily adjusted the green-liquor temperature.

	Settling time, min	Peak error
Slaker temperature		
Time lag	293	-1.10°F
No time lag	220	-0.27°F
1st-causticizer AA		
Time lag	343	-0.061 lb/ft ³ *
No time lag	265	-0.016 lb/ft ³ *
White-liquor AA		
Time lag	505	-0.061 lb/ft ³ *
No time lag	390	-0.017 lb/ft ³ *

* Expressed in terms of equivalent Na₂O

VIII. Settling times and peak errors for the lime-availability disturbance: ΔT control system with and without a time lag in measuring slaker temperature

By increasing the lime addition rate, the same amount of CaO is being added as before the disturbance. Thus, unlike for the green-liquor TTA disturbance, both white-liquor AA and causticity returned to their target values. One side effect of lower lime availability is that more solid inerts are being added, but they do not significantly affect liquor temperature, the slaking reaction, or the causticizing reaction.

Table VII shows that the AA control system clearly outperformed the ΔT control system by having a shorter settling time and smaller peak errors for both the first-causticizer AA and the white-liquor AA values. Specifically, for the AA control system, the white-liquor AA value settled within 438 min, and the peak error was only -0.037 lb/ft³ (as Na₂O) compared with 505 min and -0.061 lb/ft³ (as Na₂O) for the ΔT control system. Figure 6 shows that the liquor AA responses were faster for the AA control system because it increased the lime addition rate faster. It is also worth noting that the white-liquor AA response for the AA control system is slightly faster than for the open-loop response.

The slaker temperature response was slightly slower and had a larger peak error for the AA control system. Figure 6b shows that the AA control

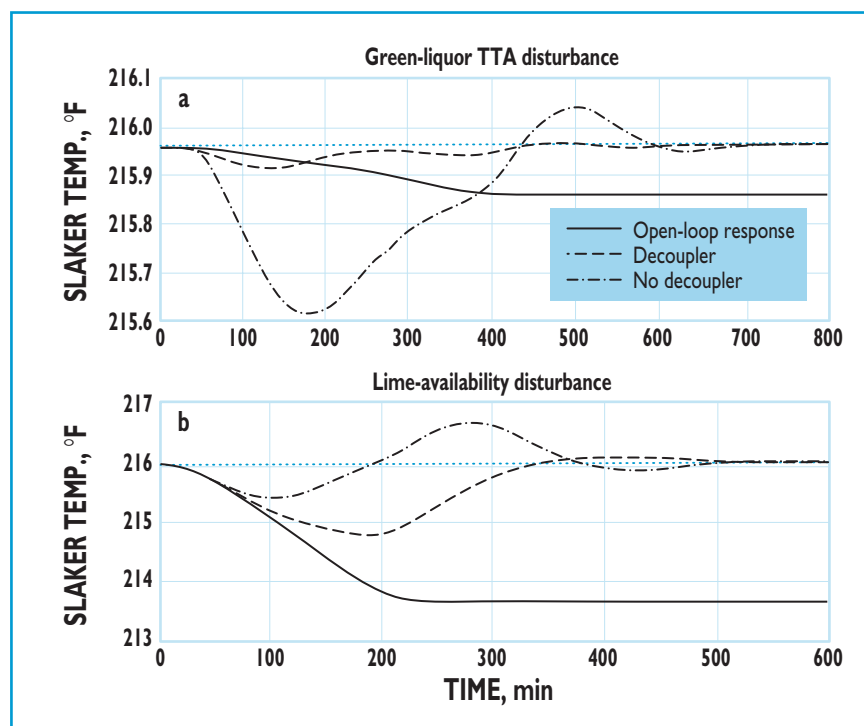
Disturbance	Settling time, min	Peak error
TTA		
Decoupler	595	-0.045°F
No decoupler	690	-0.347°F
Lime availability		
Decoupler	320	-1.20°F
No decoupler	428	0.67°F

IX. Settling times and peak errors in slaker temperature response for TTA and lime-availability disturbances: AA control system with and without a decoupler

system temporarily reduced green-liquor temperature to compensate for the known adjustment in lime addition rate. It is possible that the decoupler gain was too large, resulting in an overcompensation, which would slow down the slaker temperature response. This could be corrected by reducing the decoupler gain.

Slaker temperature measurement lag

The AA control system outperformed the ΔT control system because the G_{c1} controller for the latter system could not be tuned to respond faster because of the large time lag in measuring slaker temperature. New G_{c1} controller settings were determined for the case when there is no measurement lag, i.e., $G_{m1} = 1$. Using the direct synthesis tuning method and G_{p11} listed in Table IV, the new controller settings were determined to be $K_c = 10.7$ (lb/min)/°F and $\tau_i = 17.4$ min. The new settings differ considerably from the old settings of $K_c = 7.58$ (lb/min)/°F and $\tau_i = 48.7$ min. The no-measurement-lag case will be referred to as the “no-lag case” and the new controller settings as controller G_{c1}^* . Figure 7 and Table VIII show a comparison of the closed-loop responses of the no-lag case and the lag case for the lime-availability disturbance. All three of the responses for the no-lag case are clearly better than the responses for the lag case, which shows that the measurement lag severely limits the “achievable” performance of the ΔT control system. Comparison of Fig. 7 with Fig. 5 and Table VIII with Table VII shows that the responses for the



8. Slaker temperature closed-loop responses of the AA control system during TTA disturbance and lime-availability disturbance with and without the decoupler

no-lag case are better than those of the AA control system.

Because the duration of the slaker temperature measurement lag is proportional to the degree of sensor scaling, the measurement lag increases as the sensor ages. If controller G_{c1}^* were implemented, controller performance would still degrade over time as the degree of scaling increased. In fact, the closed-loop system containing G_{c1}^* is unstable for the measurement lag case. This problem could be corrected by periodically cleaning the sensor. However, periodical cleaning is not possible in many mills because of the location and configuration of the sensor. Often it can only be cleaned during shutdown periods. The alternative to cleaning would be to periodically “detune” G_{c1}^* by lowering the gain and increasing the reset time. This procedure would require determining a new process model or a trial-and-error tuning technique, both of which would require the intervention of plant personnel. In addition, detuning the controller will result in larger peak errors and longer settling times, as Fig. 7 clearly shows. Thus, the ΔT control system is less at-

tractive than the AA control system.

Decoupler performance

The AA control system contains a decoupler controller, but how much does it improve the closed-loop responses? Figure 8 and Table IX show a comparison of the slaker temperature closed-loop response with and without the decoupler for both disturbances. The temperature responses are for the case when the slaker temperature is scaled, i.e., when there is a large measurement lag. Active alkali responses are not shown because they did not differ significantly for the two cases. Slaker temperature variations of half a degree have little effect on first-causticizer AA and white-liquor AA. For the TTA disturbance, the response for the no-decoupler case has a large peak absolute value of the error and oscillates about the setpoint. Clearly, the decoupler improved performance in response to the TTA disturbance. For the lime-availability disturbance, the response for the no-decoupler case oscillates about the setpoint and thus has a longer settling time, but it has a smaller peak absolute value of the error than the response for the decoupler case.

Thus it is not clear that the decoupler improved performance in response to the lime-availability disturbance. However, for lime-availability step disturbances (not shown), it was determined that the oscillations became more severe and that there was little difference in the peak absolute value of the error between the two cases. Because severe oscillations reduce the life of actuators and cause downstream control loops to oscillate, the use of the decoupler is recommended.

CONCLUSIONS

Based on the results of this simulation, the AA control system is recommended over the ΔT control system. The AA control system outperformed the ΔT control system by maintaining first-causticizer AA and white-liquor AA closer to their target values during disturbances in both green-liquor TTA and lime availability. Because the AA control system infers the first-causticizer AA value, it can compensate for any disturbance that affects the AA value. In addition, the AA control system was able to maintain the white-liquor AA near its target value during the TTA disturbance, while the ΔT control system caused a larger deviation than no control. The ΔT control system can only handle disturbances that affect slaker temperature, mainly changes in lime availability. Moreover, the achievable performance of the ΔT control system can be severely limited by large time lags in measurement of slaker temperature, the consequence of sensor scaling.

The AA control system did not fully return the white-liquor AA value to its target value during the TTA disturbance. If no offset is required, then operator intervention or an additional control loop would be needed. Periodic testing of white liquor would reveal when it would be necessary for the operator to adjust the setpoint of the first-causti-

cizer conductivity (AA) controller.

Both control systems failed to control the white-liquor AA value to its target value during the TTA disturbance. White-liquor AA decreased significantly in both systems, thus increasing the sodium carbonate dead load. To maintain a target white-liquor causticity and AA values requires maintaining the green-liquor TTA at a target value and adding a sufficient amount of lime. Thus the green-liquor TTA should be tightly controlled at the smelt dissolving tank. **TJ**

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Received for review March 9, 1998.

Accepted May 5, 1998.

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