Industrial implementation of an advanced bleach plant control system

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ABSTRACT

Control strategies for the kraft bleach plant are designed to reduce production of off-grade pulp and minimize chemical consumption. This paper describes a new model-based control strategy that was implemented on the first two stages of a bleach plant that processes 800 metric tons/day of softwood kraft pulp. The new strategy—based on first-principle models—controls delignification during the chlorination stage (100% chlorine dioxide) and brightness after the first extraction stage. The model-based control strategy has increased the stability of the bleaching operation while remaining robust to process upsets. Chemical consumption is significantly lower than it was under the previous control scheme (compensated-brightness control), and standard deviation for DE kappa number dropped from 1.4 to 0.6, a reduction of 57%.

Application:

The proposed control strategy provides significantly better bleaching performance than the widely used compensated-brightness control strategy.

THE BLEACHING PROCESS INCREASES pulp brightness by removing or modifying the light-absorbing lignin that remains in the pulp after cooking and washing. This goal is achieved by applying chemical treatments in sequential stages, performed in a manner that preserves the pulp strength characteristics. In the first stage (C, C/D, or D_0), chlorine and/or chlorine dioxide are used to delignify the pulp. The delignification stage is followed by an extraction stage (E, EO, or EOP), where the alkali-soluble lignin is removed with caustic, caustic and oxygen, or caustic, oxygen, and hydrogen peroxide. In the following three stages (D_1, E_2 or EP_2, and D_2), pulp brightness is gradually increased by eliminating the chromophoric groups in the lignin.

The bleach plant is at the end of the pulping process and thus represents the last opportunity to improve pulp quality before it is shipped to the customer. High chemical costs, tighter customer demand, and tougher environmental regulations are all incentives for better bleach plant control. Advanced control schemes—based on material tracking, kappa number, chlorine dioxide residual, brightness, and kinetic models—can be developed to calculate the optimum chemical charges based on the desired product properties and process characteristics. This paper describes the development and implementation of a novel bleach plant control scheme in a kraft pulp mill. The benefits of the new control strategy are also discussed.

PROCESS DESCRIPTION

The new control system was implemented in the first two stages of a five-stage bleach plant that processes about 800 metric tons/day of softwood kraft pulp. The mill controls stock consistency and flow rate after the mix chest to maintain a target production rate.

The first bleach stage (D_0) is operated at 50°C and 3.2% consistency with 100% chlorine dioxide substitution. Residence time in the D_0 stage varies from 20 to 35 min, depending on the production rate, but even at the longest time span, the delignification reaction cannot be completed. Chlorine dioxide is mixed with the pulp slurry in an in-line mixer (Systematix). The control system for the first stage includes local feedback loops for consistency and pH control. Chlorinated stock overflows from the top of the tower and is diluted with filtrate from the first-stage washer to approximately 1% vat consistency. The stock is then washed in a rotary drum washer. Previously, the mill regulated ClO_2 flow using a compensated-brightness control strategy. The mill is now using the model-based control strategy that is described in this paper.

The extraction stage is a standard EOP stage operating at 10–12% consistency. A cascade PI (proportional, integral) feedback control loop manipulates the sodium hydroxide flow based on pH measurement. The stock is then heated to 77°C in a double-shafted steam mixer. Oxygen is added on a percentage-on-pulp basis using a diffuser at the tower inlet. Peroxide is adjusted to maintain the desired brightness target.

REVIEW OF BLEACH PLANT CONTROL STRATEGIES

Pulp bleaching is the result of two reactions—substitution and oxidation—the first being much faster than the second. Early bleach plant control strategies were based on measurements of either brightness or chlorine dioxide residual. Measurements a few minutes after the chemical addition and after the tower were used to control the chlorination tower. For instance, Danforth *et al. (1)* used two oxidation–reduction-potential probes (ORPs). The first ORP was located about 3 min downstream from chemical addition, and the second ORP was located after the tower. Other workers used the Polarox, taking advantage of its linear relationship with chlorine dioxide residual concentration. Unfortunately, these control techniques led to either underchlorinated or overchlorinated pulp. When brightness served as the controlling measurement, high-kappa-number brownstock pulps were overchlorinated, and low-kappa-number pulps were underchlorinated. When chlorine dioxide residual was the controlling measurement, the opposite occurred, with high-kappa-number pulps being underchlorinated and low-kappa-number pulps being overchlorinated *(2)*.

In the 1980s, it became clear that measurement of both brightness and chlorine dioxide residual was necessary to avoid over- or underchlorination. That led to the development of the compensated-brightness control strategy *(3)*, which is used in many North American bleach plants. This approach is based on an empirical equation that uses brightness and chlorine dioxide residual (and sometimes production rate, temperature, and pH) to calculate the "compensated brightness," which in turn is used to control the chlorine dioxide addition rate. The advantages of using compensated brightness over residual or brightness control have been discussed by Baines *(4)* and Baker *(5)*. Mill implementation and results have been discussed by Beaupre *(6)* and Bleackley *(7)*. Some mills have attempted to enhance this approach by applying a compensated brightness before and after the tower. The idea was to use brightness and residual measurements before the tower to compensate for variations in incoming kappa number, production rate, temperature, and carryover while using brightness and residual after the tower to compensate for slow process variations. However, this has not produced any significant improvement *(5)*.

In the past few years, with the availability of more powerful computers and new sensors such as on-line kappa number analyzers, bleach plant control is moving towards model-based control strategies. Pulp tracking (assuming plug flow behavior) and polynomial regressions have been used to calculate the degree of delignification in the chlorination tower.

NEED FOR A NEW CONTROL APPROACH

Brownstock kappa number, production rate, and temperature are moving targets, and chemical dosages in the bleach plant must be adjusted to achieve the desired targets for the final pulp. The compensated-brightness control strategy was unable to deal with variations in incoming kappa number, resulting in off-grade pulp. Moreover, feedback control is difficult because of long and varying delays in the tower.

Given these limitations, we attempted to develop a new control strategy based on a mechanistic model that included the hydrodynamic behavior of pulp flow inside the towers as well as the kinetics of the delignification and bleaching reactions. The goal was to develop a model that could calculate the optimum dosages of ClO_2 and H_2O_2 based on the operating conditions and the required targets for pulp quality.

MECHANISTIC MODELS

Bleaching tower hydrodynamic model

A lithium chloride tracer method was used to study the pulp flow behavior inside the D_0 and EOP towers in terms of transport lag and mixing. The E-curves showed that the pulp flow in the towers deviated quite significantly from pure plug flow and that mixing was substantial. It was therefore decided to use a plug flow in series with a continuously stirred tank to approximate the response signals of all key variables, such as chemical concentrations, consistency, kappa number, and brightness. For the D_0 tower, which operates at 3.2% consistency, the percentage of mixing vs. plug flow is 25% vs. 75%. For the EOP tower, which operates at 12% consistency, the percentage of mixing vs. plug flow is 14% vs. 86%.

Chlorine dioxide delignification model

When developing a mechanistic model to predict kappa number, brightness, and chlorine dioxide residuals from operating conditions, one needs to understand the stoichiometry and the kinetics of the chemical reactions. The accuracy of the kinetic model used in the control strategy is of critical importance, since the performance of the entire control system depends on the model predictions.

Research in the area of bleaching reaction kinetics has not caught up with the rapid changes that have occurred in recent years. Although many papers have been published on chlorine delignification and chlorine dioxide substitution *(8–15)*, only a few papers in the literature are devoted to the kinetics of delignification using 100% chlorine dioxide *(14)*.

Site-specific models were developed by collecting pulp samples at different kappa numbers from the mill and then performing a series of experiments at different chlorine dioxide charges and temperatures. Based on the experimental data, a kinetic model structure—similar to the one proposed by Ackert *(8)*—was selected to account for the fast and slow reactions as well as the presence of unreactive or "floor" lignin. Further details on the experimental procedure and the kinetic model can be found in a paper by Tessier and Savoie *(16)*. From this kinetic model, a second model more suitable for process control was derived *(17)*. The model predicts D_0-stage kappa number and brightness and chlorine dioxide consumption, as seen in Eqs. 1–3, respectively.

$$D_0\ \text{kappa}(t) = \text{unbleached kappa} - 9 - K_k(1-\exp^{-t/\tau}) \quad (1)$$

$$D_0\ \text{brightness}(t) = \text{initial brightness} + 8.5 + 1.66\,K_k(1-\exp^{-t/\tau}) \quad (2)$$

$$ClO_2\ \text{consumption}(t) = 1.45 + \frac{K_k}{5.8}(1-\exp^{-t/\tau}) \quad (3)$$

where

K_k = static gain for kappa number
t = time
τ = time constant

A least-squares optimization technique was used to estimate the static gain K_k and the time constant as functions of temperature and kappa factor. The values of these parameters depend on wood species and are mill specific. **Figure 1** shows the good agreement between the model predictions and the experimental data at 50°C for different combinations of incoming kappa number and kappa factor.

Extraction model

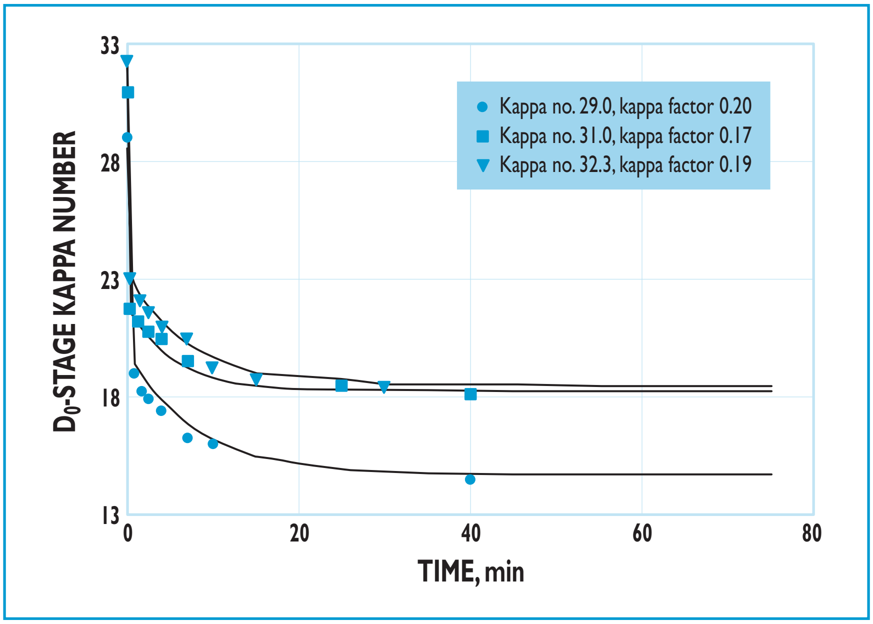
As the pulp progresses from the first to the second stage (where the first extraction takes place), lignin is further removed and modified by eliminating the chromophoric groups. The controller thus must be able to predict not only the kappa number but also pulp brightness so that the mill can track the brightness development, which starts in the extraction stage and continues into the D_1, EP_2, and D_2 stages. Since the residence time in an industrial extraction tower is long enough for the reaction to be completed, a steady-state model was chosen to represent the extraction stage. Equations 4 and 5 are empirical expressions for pulp kappa number and brightness after the first extraction stage. These equations were derived from experimental data for hydrogen peroxide charges between zero and 0.75%.

$$\text{DE kappa} = D_0\,\text{kappa} - 12 - 1.43(\%H_2O_2) \quad (4)$$

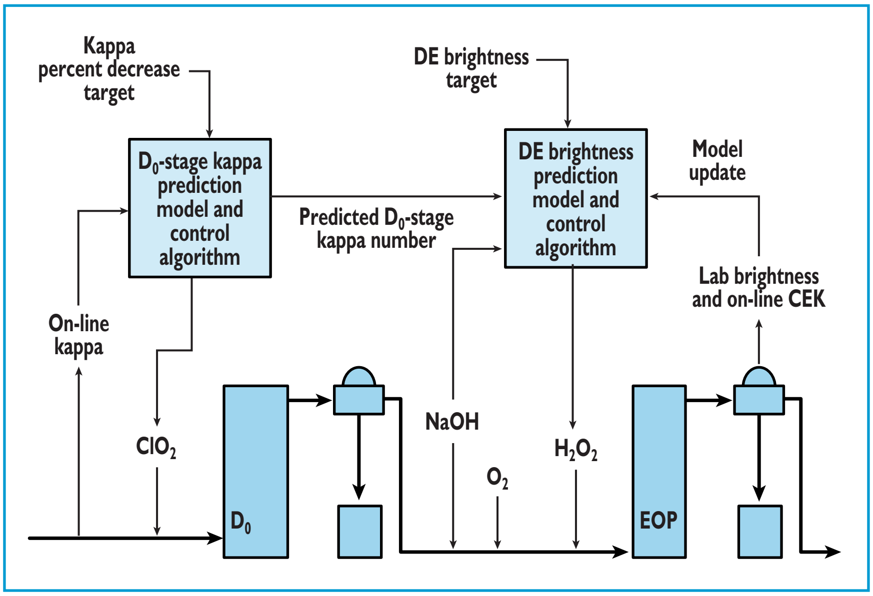
$$\text{DE brightness} = D_0\,\text{brightness} + a + 16.0(\%H_2O_2) \quad (5)$$

where

a = 9 + 4(% NaOH – 1.5%) for caustic charges between 1.5% and 4%.



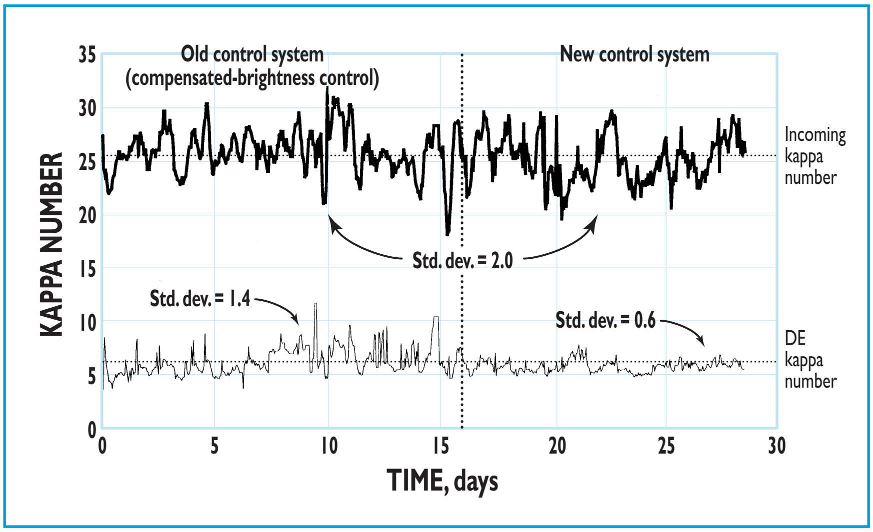
1. Experimental data and model predictions of kappa number exiting the D_0 stage (50°C) for various combinations of brownstock kappa number and kappa factor



2. Control strategy

PROPOSED CONTROL STRATEGY

The supervisory loops of the proposed control strategy for the front end of the bleach plant are shown in **Fig. 2**. The figure does not show the local feedback loops for controlling flows, consistency, and pH in the D_0



3. Brownstock kappa number and DE kappa number before and after implementation of the new controller

stage. This control strategy was described in a patent application submitted by Noranda Forest.

Control strategy for the D_0 chlorination stage

The production rate in the first stage is calculated from pulp flow rate and consistency measurements, taking into account fiber shrinkage in each stage. The production control program provides a method of ramping the production rate to minimize its effect on pulp quality. Incoming kappa number to the first stage and DE kappa number after the second stage are measured by a kappa analyzer every 15–25 min.

The objective of the control strategy is to maintain a constant percentage of delignification across the D_0 stage in order to share the load between the front end and back end of the bleach plant. The control algorithm calculates the ClO_2 charge setpoint from our kinetic model using the incoming kappa number measurements, the desired percentage of delignification, and the tower temperature and residence time. The ClO_2 flow setpoint is then calculated from the production rate and ClO_2 charge setpoint. The control algorithm was written in Fortran and runs on a VAX station that communicates with the mill's distributed control system (DCS) and CIM21 data management system, allowing process values to be read by the program and setpoints to be returned to the DCS and local loops. Several features have been added to check for missing and erroneous data, bleach plant shutdowns, communication errors between the VAX and the millwide information system, and bumpless transfer when switching from manual to automatic control. All of the input variables to the program are filtered to remove noise.

Control strategy for the EOP extraction stage

The main objective of the second stage is to control the EOP brightness by manipulating the peroxide charge. The latter is calculated from the extraction kinetic model, as shown previously. Since there is no kappa number or brightness measurement after the first stage, the control strategy for the second stage is based on the predictions from the first-stage kinetic model. A pulp-tracking subroutine was developed to account for varying delay in the first stage as a result of changes in production rate. Pulp tracking is a data-logging and time-delay-modeling program. It tracks the movement of stock through the towers as well as process variables—consistency, temperature, chemical charge, kappa number—associated with the stock entering the first stage. Process information is stored by successive integration of arrays, providing a complete history of the stock from the time it enters the D_0 stage until it exits the EOP stage.

The DE kappa number and DE brightness predictions are based on the actual process, and material tracking allows the dead-time compensation to be dynamically adjusted based on the production rate. When a new DE kappa number measurement is available from the on-line kappa analyzer, it is aligned with the correct process conditions. It is important to time-synchronize the data as the model is updated by adjusting the model parameters based on DE kappa measurements. The difference between measurements and predictions are filtered and used to adjust the model parameters. When available, brightness measurements can be used to adjust the brightness prediction model.

RESULTS

The proposed advanced control strategy was implemented on the VAX station linked to the mill DCS, and a graphic interface was designed for the operators. The operators can enter the desired percentage of delignification for the first stage and the EOP brightness target. The control system can be activated on both towers or on a single tower. In addition, predictions for D_0-stage kappa number, brightness, and residuals from the D_0 pulp tracking model and predictions for DE kappa number and DE brightness from the EOP pulp tracking model are displayed on the screen, providing the operators with "soft sensor" measurements of the pulp properties.

The operators have adapted well to the new control strategy, which differs significantly from the compensated-brightness controller that they had been using for years. **Figure 3** demonstrates the benefits of the new strategy compared with the compensated-brightness control strategy that is widely used throughout the industry. The new control strategy has reduced standard deviation of DE kappa number from 1.4 to 0.6, a reduction of 57%. Moreover, the controller has been robust to process upsets. At present, the control strategy is limited to the first two stages, but it will eventually be extended to the back end of the bleach plant.

CONCLUSION

A model-based control strategy has been implemented on the first two stages of a five-stage bleach plant. The new system controls delignification across the first chlorination stage and brightness exiting the first extraction stage. The controller has improved the stability of the bleaching operation while remaining robust to process upsets. Standard deviation of the extracted DE kappa number has been reduced from 1.4 to 0.6, a reduction of 57%. The bleach plant's consumption of chlorine dioxide has also dropped significantly since implementation of the control system. **TJ**

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