O PAPEL vol. 79, num. 2, pp. 65 - 72 FEB 2018

BLEACH PLANT OPTIMIZATION UTILIZING NOVEL MEASUREMENT TECHNOLOGIES COMPLEMENTED WITH ADVANCED PROCESS CONTROL

Autors: Akhlesh Mathur[1], Niclas Andersson[2], Daniel B. Smith[3], Renato Onofre[4], Gabriel Morgan[5]

[1] *ASPAC Fiber Segment Director, BTG Instruments, Singapore*
[2] *BTG Instruments Research and Development Director, Sweden*
[3] *VP Automation, Capstone Technology, Seattle, WA, USA*
[4] *South America Manager, Capstone Technology, São Paulo, Brazil*
[5] *South America Fiberline Manager, BTG Americas, São Paulo, Brazil*

ABSTRACT

Unit operations in a fiberline are designed to selectively remove lignin to achieve a pulp with the desired brightness, cleanliness and strength. Pulp being a commodity, there is always a pressure to reduce costs. The primary focus is generally to reduce wood costs but efforts to reduce bleaching chemicals, the second biggest cost contributor, cannot be ignored.

Conventional bleach plant process control is based on the lignin content of the pulp fibers expressed as kappa number, combined with brightness measurement in the bleaching stages. There's compelling evidence that carry-over consumes bleaching chemicals (Chlorine dioxide, in short ClO_2). In the absence of carry-over measurement, mills compensate by applying a high operator bias to cover peak carry-over demand, which results in higher bleaching costs. To overcome this challenge, the pulp industry is currently transitioning from conventional fiber kappa number measurement using a traditional multipoint analyzer to a new total kappa measurement using an inline Bleach Load Transmitter for ClO_2 charge control. This way, the impact of carry-over lignin is also included in the control of chemical charge. This continuous bleach load signal minimizes operator bias and delivers significant bleaching chemical savings.

Manipulation of multiple process variables is required to achieve effective bleach plant control and it's extremely challenging to optimize each of the controlled variables to maintain the process close to target. While it's of utmost importance of have the sensors functioning accurately and regulatory control loops in place, it is practically impossible for operators to manually optimize bleaching chemicals to achieve final brightness at minimal cost. To overcome this challenge, Multivariable Advanced Control System (MACS), a proven advanced control platform, has the potential to deliver large savings to mills. MACS uses dynamic process models to account for the effect of bleach load disturbances on downstream kappa number and brightness, and manipulates the ClO_2 dose to compensate for these disturbances. MACS corrects for unmeasured disturbances via feedback control, and accounts for varying process delays and non-linear bleaching curves via real-time model adaptation. MACS also optimizes the bleach load applied at each stage to minimize bleaching cost for a given final brightness.

This paper highlights the advantages of a synergistic approach to optimizing bleach plants by utilizing proven, novel and differentiated measurement technologies with advanced process control strategies. Some case histories taking this approach are also included.

Keywords: Kappa number, Lignin, Bleach Load Transmitter, Carry-over and Multivariable Advanced Control System

INTRODUCTION

Pulp being a commodity, forces pulp makers to constantly be on their toes to look for areas of improvement that can reduce their operating costs, improve quality (and variability) and strengthen their mill's environmental profile. Wood, chemicals and energy costs capture the lion's share on a mill's bottom line and, hence, indicate key survival index [1].

A chemical fiberline process is designed to selectively remove lignin from wood chips to obtain pulp with the specified brightness, cleanliness and strength at the lowest possible cost. Each unit operation, from cooking through to bleaching, is designed to charge chemicals and maintain a pre-determined process

Corresponding author: Gabriel Silva Morgan da. BTG Americas. Rua Nicola Rollo, 151, apt 254-A, São Paulo, SP. CEP:05726-140. Brazil. Phone: +55 11 99312 8898. E-mail: gabriel.morgan@btg.com

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condition to obtain maximum lignin dissolution with minimum fiber strength degradation. For highest possible efficiency of each unit operations, the end-result (kappa / brightness) must be measured with highest possible accuracy, reliability and frequency for the process operation to take corrective measures when process deviates from the set-point.

Wood costs typically account for 40-60% and bleaching chemical costs account for 5-15% of total variable cost. The relationship between the pulp lignin content of kraft pulp (signified by kappa number) and cooking yield is well established [2], thus a higher cooking kappa number principally corresponds to a higher cooking yield for a given cooking system.

A bleach plant is designed to (i) remove any lignin carrying forward with the pulp from cooking and oxygen delignification in the first bleaching stage, (ii) oxidize the remaining lignin to brighten the pulp and achieve target brightness through application of various bleaching chemicals, and (iii) achieve the target brightness with target viscosity, minimum effluent load and maximum cleanliness. The cost of lignin removal increases from cooking through to bleaching, hence, controlling cost of bleaching chemicals to achieve a desired brightness cannot be ignored.

METHODS

Typical Challenges with Bleaching Process Control

Some of the common challenges in achieving target brightness with minimum variability and lowest cost in a conventional bleach plant are as follows:

a) Wood composition variability: Every wood species has different bleachability, so it's desirable to have a constant furnish mix for a bleach plant to operate optimally. But in reality this could change, under which circumstances, making sure that the kappa coming out of unbleached plant should be kept as stable as possible. While all the variables associated with raw material like moisture, bulk density, source, age, composition, etc. are to some extent "homogenized" in cooking and oxygen delignification, the expectation is that these variables are "dealt with" in bleaching by manipulating the bleach plant variables appropriately.

b) Cooking, Brown Stock Washing (BSW) & Oxygen Delignification efficiency variability: Selecting the optimum target cooking kappa number for bleached pulp production requires balancing yield in cooking and bleaching with e.g. recovery boiler solids load, bleaching costs, wood costs, oxygen delignification optimization, pulp mill throughput and the desired final papermaking qualities of the pulp. Running cooking operations optimally to achieve steady cooked kappa number is extremely important. In brown stock washing (BSW), the dissolved lignin from cooking needs to be washed off with optimum dilution factor so that the sweet spot of optimum carry-over with minimum evaporation costs and lowest bleaching costs is achieved. Further, oxygen delignification can be seen as a shock absorber between cooking and bleach plant. Running oxygen delignification plant optimally requires managing multi-variables and to react to situations to keep the balance between cooking and bleaching. Any variability coming from unbleached section (fiber kappa, carry-over, shieves, dirt, etc.) is amplified in the bleach plant and leads not only to higher bleaching costs but amplified variability and possible downgrades. Mistakes made in cooking, BSW and oxygen delignification are a lot more expensive and difficult to correct in bleach plant.

c) Controlling brightness development using fiber kappa alone (Effect of carry-over): Conventional bleaching control relies heavily on measurement of fiber kappa feed to bleach and using fiber kappa to determine oxidant charge using kappa factor-based control. While the fiber kappa number indeed is a critical parameter, there's enough compelling evidence that the carry-over of dissolved lignin from cooking and oxygen delignification can be very high but, more importantly, it often varies significantly [4, 8-11]. It has been observed that filtrate kappa can contribute 10-50% of fiber kappa and in most of the mills it has a lot more variability.

As shown in Figure 1, the carry-over consumes ClO_2 – one kappa number of filtrate consumes same amount of ClO_2 as one kappa number of fiber. Carry-over today is not a direct measurement and often surrogate values as soda loss, conductivity, etc. have been used, which could be important from a soda balance perspective (unbleached section) but do not directly quantify the organic carry-over. Chemical Oxygen Demand (COD) measurement is the only measurement that correlates well with dissolved lignin but is measured in lab today. Lab measurements take time (8+ hours) and, hence, cannot be used for proactive control. For bleach plant, the most significant variable that determines ClO_2 charge is the total lignin concentration, i.e. fiber kappa + filtrate kappa. ClO_2 being the most expensive input ($/T), any effort to reduce ClO_2 has a huge payback. Once ClO_2 charge reduces, it is normal to see reduction in NaOH and H_2O_2 as well.

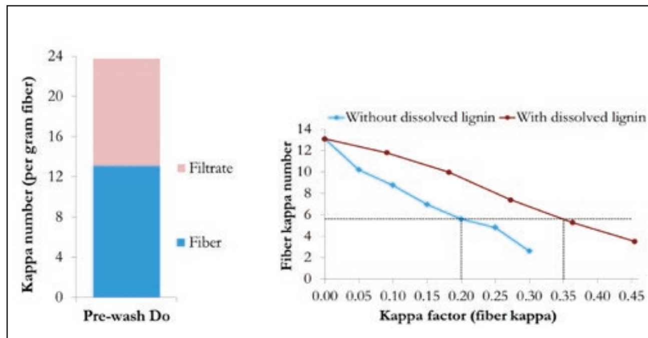

Figure 1. Fiber kappa number vs. kappa factor for well washed pulp and unwashed pulp, respectively, from pre-D0.

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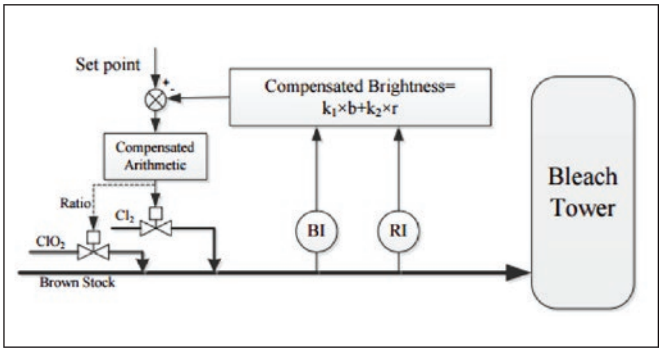

Figure 2. Compensated brightness control schematic

d) Compensated brightness control strategy: Conventional bleach-plant process control has been based on what is referred to as compensated brightness control strategy [5]. This control involves measurement of brightness and Cl_2/ClO_2 residual at the C / D0 stage using inline or offline measurement just after the chemical mixer and just before the C / D0 pretube/tower as shown in Figure 2.

This concept was developed 30 years ago when Chlorine (Cl_2) gas was used for bleaching. Since Cl_2 is a very fast-acting oxidizer, the idea was to measure brightness development a few seconds after addition into the pulp and see how "reactive" the pulp is. This brightness measurement was used as a quick feedback to vary Cl_2 addition. Further residual measurement just before entering the tower helped to correct the Cl_2 addition due to changing furnish or variability coming from brown stock including carry-over. Today most mills have switched over from Cl_2 to ClO_2, which is far slower (about 3 times) in reactivity though more selective. However, the industry has still been using compensated brightness control – which is not effective since there's hardly any brightness development with ClO_2 few seconds after addition. There are some other inherent flaws in brightness measurement after chemical mixer and residual measurement accuracies that further make compensated brightness control not work perfectly in all conditions. As shown in Figure 3, implementation of this model was highly dependent on operator decision-making and experience. Since every operator has different skills and experience, most mills using compensated brightness control with ClO_2 face varying bleach plant performance, using higher operator bias and much more frequent manual adjustment of chemicals charge. This leads to overall higher bleaching chemicals cost, not to mention higher brightness variability.

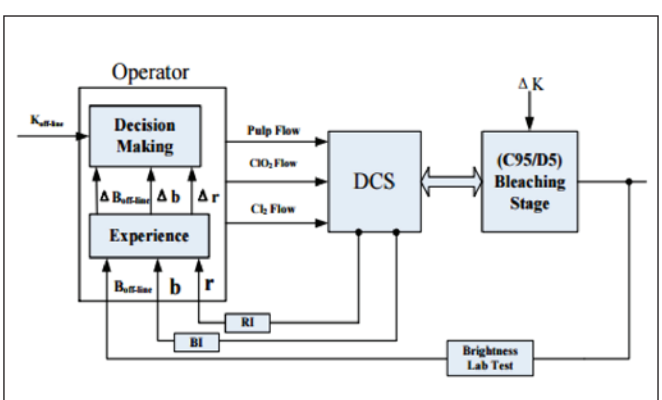

Figure 3. Compensated brightness control logic

e) Measurement update rate: All process controls require some sort of measurement to work. Online multi-point kappa analysers have been traditionally used for determination of lignin content using measuring principles employing absorption of ultraviolet light. Such systems have been the industry standard since their introduction in the 1980's. The normal measurement update rate achieved is around 30 minutes, but it naturally depends on the number of positions and sequence program. Measurement update rates of 30 minutes and above are not suitable for optimum bleach plant utilizing multiple stages since the operator assumes that the primary measured variable kappa number and brightness is the same across the measurement cycle and so in most cases, either one over-dose or under-dose. This cumulative operator bias due to lack of frequent measurement update causes higher bleaching costs. The situation is even more challenging when the multi-point analyser ages and loses reliability, in which case the response to a variability can easily be few hours, which is an extremely expensive approach. As an alternative to multi-point kappa analysers, inline (real time) sensors allow process control systems to (i) react to all incoming quality disturbances both slow and fast, (ii) to more accurately predict downstream quality since there's no "missing" information between the samples, and (iii) react in a more timely and effective manner to unexpected changes in downstream quality. Figure 4 shows simulated data illustrating the advantages of using inline transmitters. To compensate for the weaknesses of multi-point kappa analysers, it's common to install additional inline instrumentation (e.g. brightness sensors), which are used to estimate the kappa between samples, but result in a more expensive and complicated process control solution.

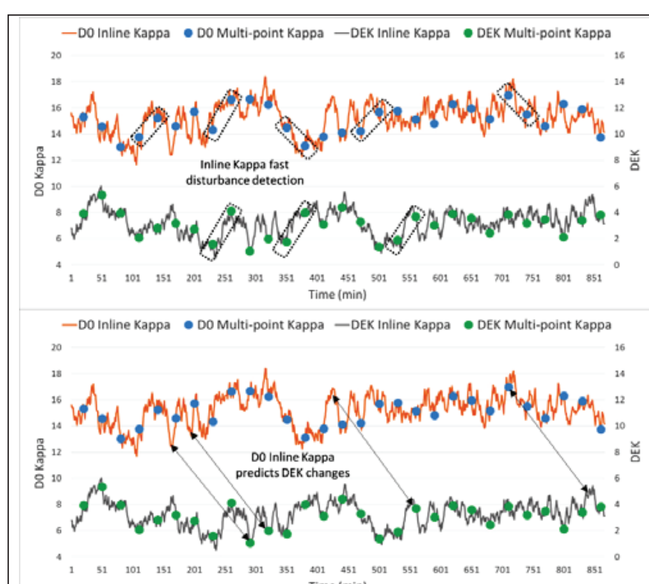

Figure 4. Advantages of inline kappa sensors

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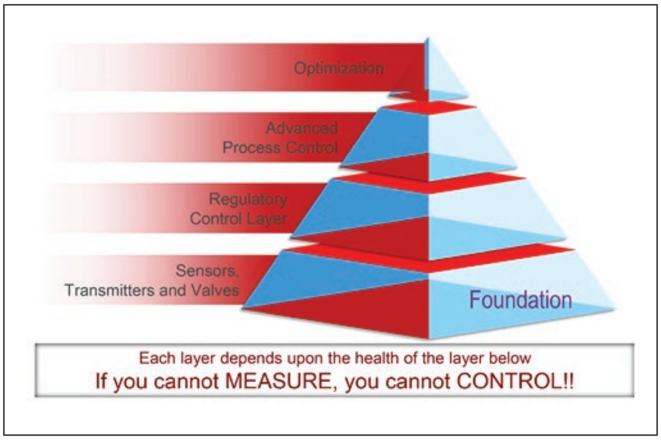

Figure 5. Hierarchy of process control

f) Process control challenges today: ECF Bleach plant has multiple stages and each stage has to deal with multiple manipulated and control variables. Manipulation of multiple process variables required to achieve effective bleach plant control is an extremely challenging task to optimize each of the controlled variables to maintain the process close to target. Efficiency of each bleaching stage relies heavily on accurate measurement and control of basic process parameters like consistency, temperature, pH, pressure, flow, etc. In the absence of accurate measurement and control of these basic functions, the overall process control, pulp quality and economics of operation suffer.

While it is of utmost importance to have sensors functioning accurately and regulatory control loops in place, it is practically impossible for operators to manually optimize bleaching chemicals to achieve final brightness at minimal cost.

In order to effectively control quality and optimize bleaching chemicals using regulatory control only, an operator would have to (i) continuously adjust chemicals at each stage to account for the incoming pulp quality from the previous stage, (ii) account for the long time delays and non-linear relationships to adjust for unexpected changes in the pulp quality leaving the stage, and (iii) trade off bleaching chemicals such as ClO_2 and H_2O_2 to minimize the cost of brightness at a given stage (iv) all the while working towards an optimum chemical split between the stages. In addition to this the operator would need to adjust the chemicals used to control the pH at each stage by compensating for upstream chemical and pH indicators that effect downstream pH. Needless to say, this is not a realistic expectation, so instead of this, operators tend to overdose chemicals at the front of the bleach plant to account for incoming quality changes.

If all above challenges are not handled appropriately, the bleach plant suffers from:

- Poorly optimized yield and production rate
- Off specification pulp production (brightness, viscosity, dirt, etc.)
- High chemical cost due to over-bleaching
- Unstable process

RESULTS AND DISCUSSION

Latest Trends in Bleach Plant Control

a) Total Lignin Management (Measurement Strategy): Overcoming the gaps in measurement technology, it is now possible to measure lignin in various forms (i.e. associated with fiber called fiber kappa; in dissolved form called dissolved lignin; total lignin called total kappa) as shown in Figure 6 and reported previously [1, 4, 6, 7, 13].

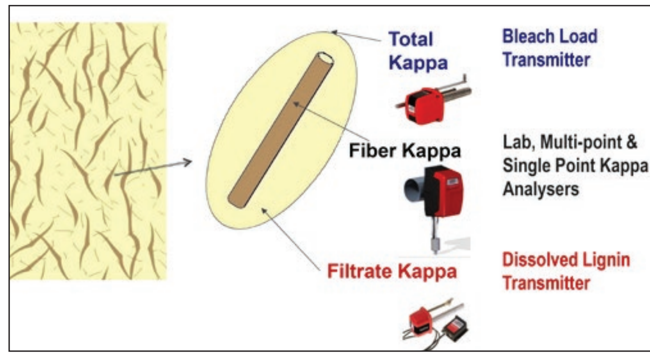

Figure 6. Tools available for Total Lignin Management in a fiberline

The Bleach Load Transmitter measures total kappa, the primary control variable for bleach plant. The sum measurement of fiber kappa and filtrate kappa (carry-over), referred as TOTAL kappa, is used as a feed forward control to determine ClO_2 charge in D0 and D1 stages to optimize the bleaching chemical consumption.

The bleach load based chemical charge control offers potential for optimization of ClO_2 due to (i) total kappa instead of fiber kappa alone, (ii) continuous versus cyclic measurement, (iii) the opportunity to reduce variability and off grades, and (iv) reducing bleaching chemicals costs.

b) Bleach plant process control strategy: As shown in Figure 7, the sharpest kappa number decline happens up to and including the first bleaching stage (D0) whereas the brightness development gradient is highest after extraction stage. From this perspective, the industry accepted process control strategy for a chemical fiberline is to measure and control the process using kappa number from cooking through to first bleaching stage (D0) and using brightness to control the process from extraction stage onwards.

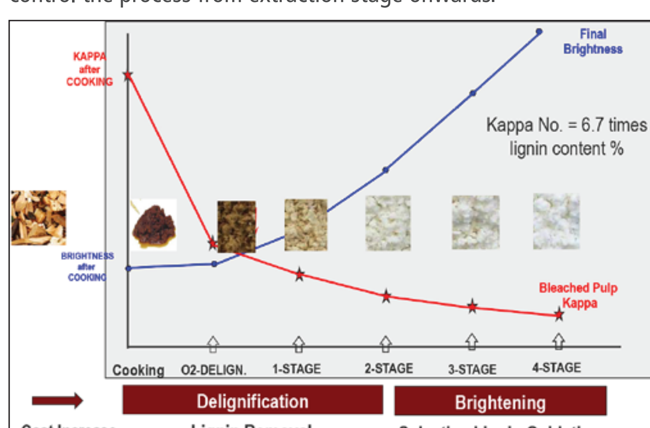

Figure 7. Kappa & brightness development across fiberline

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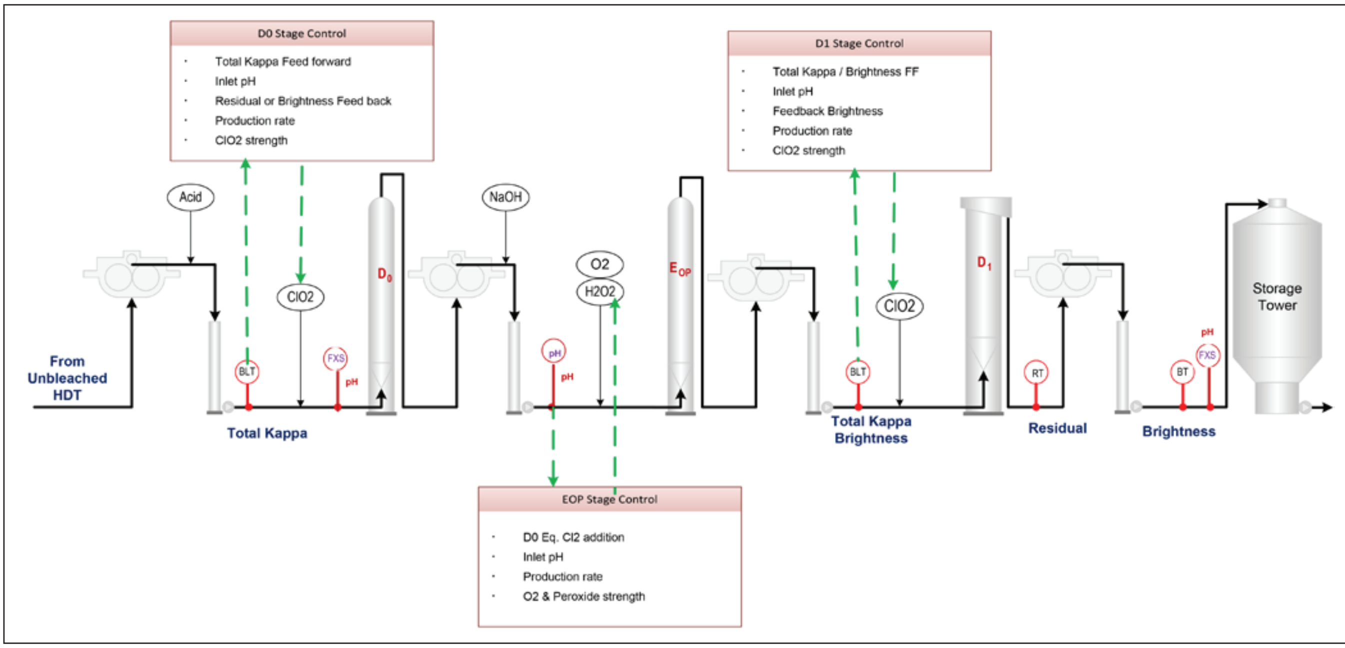

Figure 8. Typical bleach plant measurement & control strategy

Figure 8 is a typical 3-stage ECF bleach plant measurement and control strategy utilizing inline total kappa and brightness measurement for optimum bleach plant control.

Experience has shown that together with well-performing process regulatory controls, substantial economic gains can be achieved from these newly developed lignin sensors.

Due to challenges associated with bleaching as discussed in section 2, industry is in the process of transitioning from conventional kappa / brightness-based bleach plant control to a total kappa and brightness-based control utilizing the novel capability of these new sensors.

c) Model Predictive Control: Model Predictive Control (MPC) has been gaining acceptance in industry as the control technology of choice for Kraft bleach plant control. MPC is a multivariable control algorithm that uses an internal dynamic model of the process, a history of past control moves and an optimization cost function over the prediction horizon to calculate the optimum control moves [12]. As discussed previously [13], MPC is well suited for bleach plant control since it naturally addresses many of the control challenges encountered in a bleach plant. Some of the typical features of commercial MPC packages that apply to bleach plants include:

- Inherently decouples interacting control relationships such as the effect of ClO_2 and H_2O_2 on kappa and brightness, or ClO_2 and NaOH on pH.
- Includes feedforward relationships, such as the impact of bleach load on downstream kappa and brightness, or inter-stage brightness on final brightness.
- Ability to manage process constraints that do not have a fixed set-point, such as DEK, inter-stage brightness, pH, or ClO_2 residual.
- Utilizes dynamic models account for long dead-times and slow dynamics through bleach and extraction towers.
- Option to program the dynamic models to adjust for non-linear bleach curves and variable process dynamics through bleach towers due to changing production.
- Typically includes economic optimization capabilities to minimize the cost of achieving target brightness, by optimizing the ClO_2 distribution between stages, and by trading off ClO_2 versus H_2O_2 depending on their price and effectiveness.

Commercial MPC packages are convenient and practical to use. For example, Multivariable Advanced Control System (MACS™) is a suite of software tools for the design and implementation of MPC applications. The MACS platform provides software modules for all phases of MPC implementation, including data acquisition, model identification, controller design and simulation, and real-time control.

It is easy to modify the control structure and objectives compared to advanced regulatory control solutions that normally have a fixed structure. MACSproject is a graphical tool for the design and tuning of multivariable controllers. An intuitive interface and common data structure with MACSmodel allows point-and-click building of a controller. Graphical feedback of simulation results simplifies and speeds controller tuning and design analysis. Figures 9 and 10 show the MACSproject configuration interface and example simulation results respectively.

MPC requires good dynamic models between each of the manipulated / feedforward variables and the controlled variables. MACSmodel is a graphical tool for process data analysis and model identification. The software interface guides the user through model development and validation. Database archiving of raw data and

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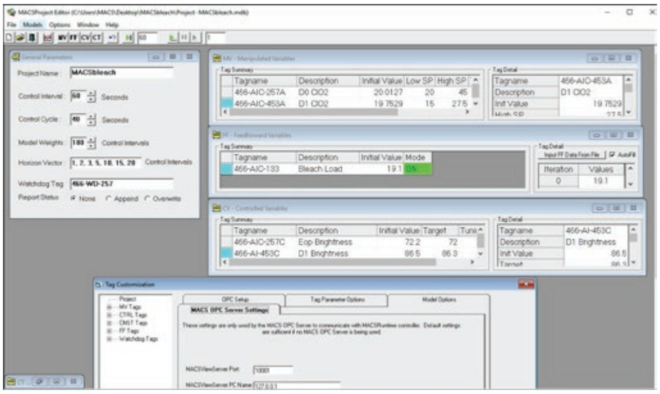

Figure 9. MACSproject Configuration Interface

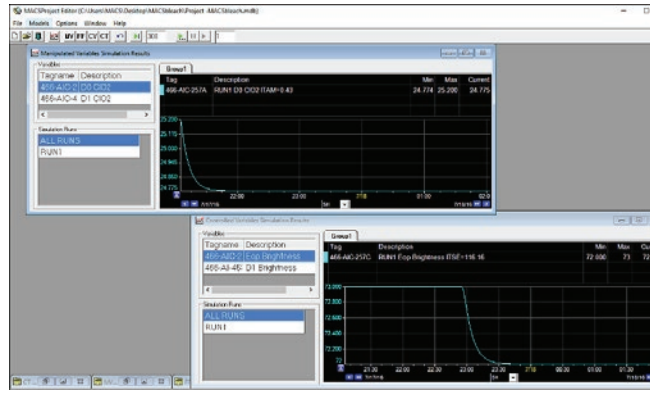

Figure 10. MACSproject Simulation Results

models facilitates project management and long-term support. Figures 11 and 12 show a dynamic model generated between D0 ClO_2 and D0 outlet brightness using MACSmodel.

MPC is well suited for feedforward control. The key to effective feedforward control is good process identification. After the models are built, it is simply a matter of adding the models into the control matrix. For example, inline total kappa before the D0 stage is an MPC feedforward variable used to predict future changes in DEK and EOP brightness.

Process constraints are variables that are not held to a set-point but held between an upper and lower limit. The ability to add process constraints is very useful when trying to avoid undesirable operating conditions, as well as for high-level optimization. In bleach plant control it might be desirable to control pH in a range rather than a fixed set-point or similarly hold ClO_2 residual between a high and low limit. For total ClO_2 cost reduction, controlling inter-stage brightness between high and low limits or DEK between high and low limits, allows for ClO_2 optimization between the stages.

It is common to encounter process models that change as a function of operating conditions. Some examples include (i) the process gain between ClO_2 and brightness decreases as the dosage is increased, and (ii) when pulp inventory or production changes, the process delay changes. For these situations, many MPC packages include the ability to program real-time changes to the dynamic models. By making these real-time adjustments, MPC can be tuned to be more aggressive without risking control oscillation. Figures 13 and 14 show non-linear bleach models fit using methods described by McDonough et al. [14]. MPC should be configured to account for the decreasing process gain as ClO_2 dose increases.

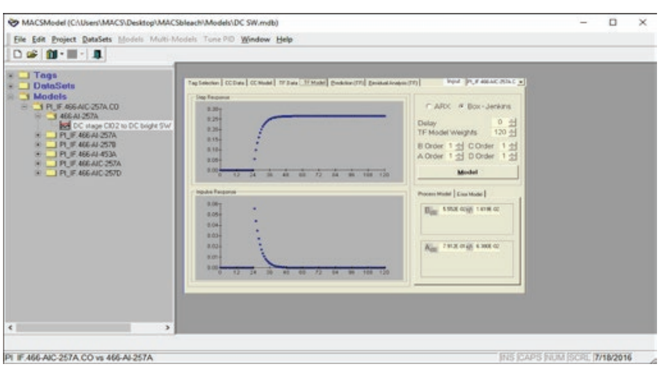

Figure 11. Step Response Model between D0 ClO_2 and D0 Outlet Brightness (Gain 0.5, Delay 20 min, Time Constant 5 min)

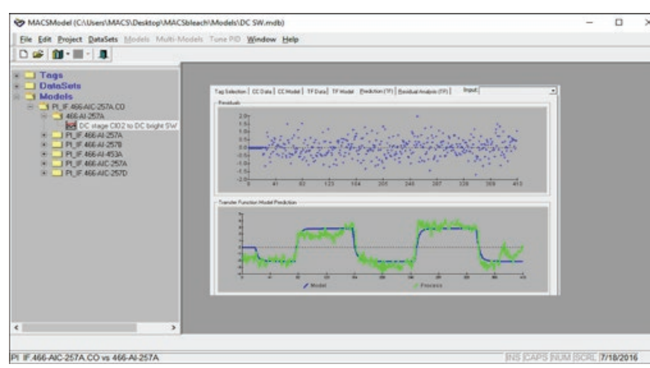

Figure 12. Transfer Function Model Prediction between D0 ClO2 and D0 Outlet Brightness (Gain 0.5, Delay 20 min, Time Constant 5 min)

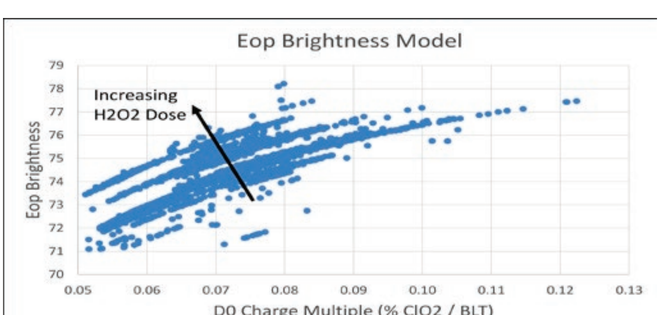

Figure 13. Eop Brightness as a function of D0 Charge Multiple (multiple curves depending on Eop H_2O_2 dose)

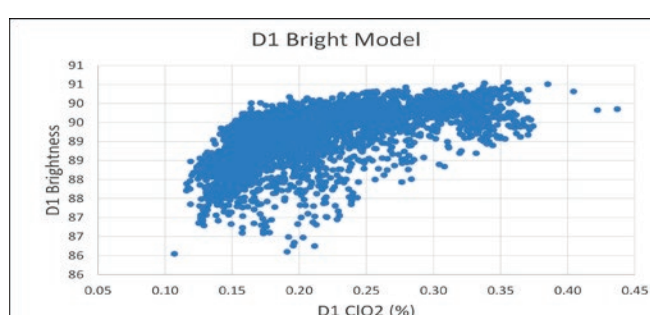

Figure 14. D1 Brightness as a function of D1 ClO2 dose (multiple curves depending on Eop Brightness)

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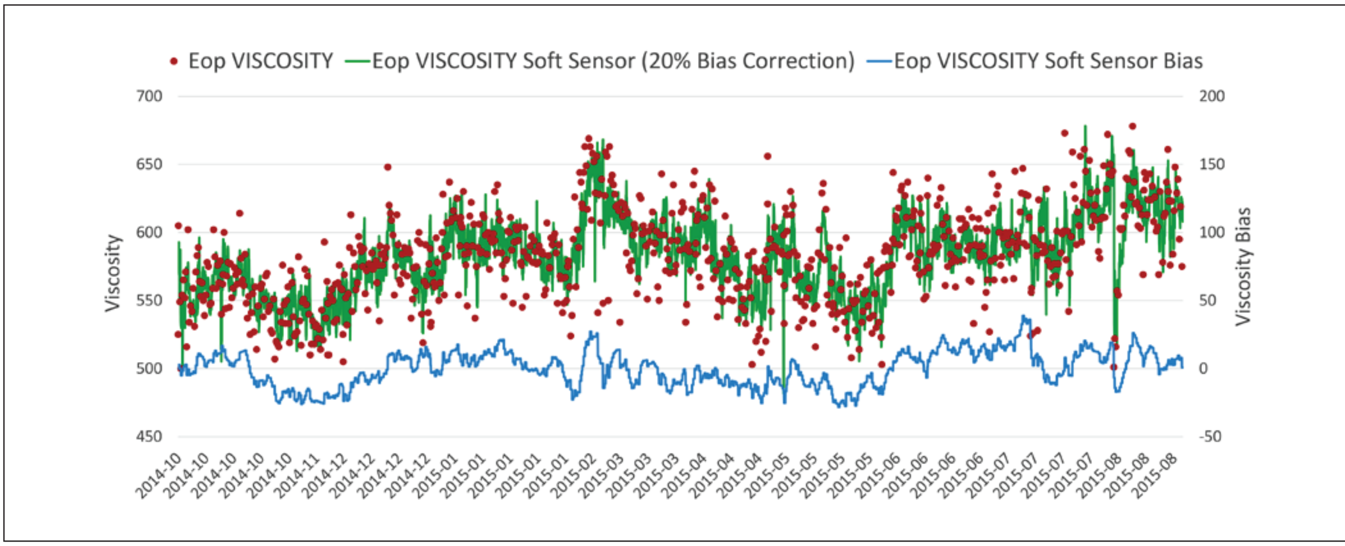

Figure 15. Viscosity Soft Sensor (PLS Model)

So-called soft sensors are a common component of advanced control solutions in general including MPC applications. A common example is to implement pH soft sensors, which are simply the pH sensors adjusted in real time using a percentage of the error between the pH soft sensor and the pH lab measurement. Certain quality parameters, such as viscosity, are only measured in the lab. Soft sensors can also be used to estimate these quality parameters, using techniques such as Partial Least Squares Regression (PLS). Figure 15 shows an example of a viscosity soft sensor based on a PLS model, using chemical dosages, pulp quality analyzers, production rate, etc. as inputs.

Bleaching Cost Optimization

Many MPC packages have the ability to perform cost optimization. Linear Programming (LP) optimization applies to control problems where there are more manipulated variables than controlled variables or some controlled variables are controlled to ranges rather than set-points. The optimization takes advantage of these extra degrees of freedom. As described above for bleach plants the extra degrees of freedom for ClO_2 optimization are included by controlling inter-stage brightness to a range rather than a set-point. Figure 16 shows an example cost optimization analysis from a recent case study. In this example, more ClO_2 should be shifted from D0 to D1 to achieve the same final brightness at lower ClO_2 usage. A brightness target shift is also shown, where ClO_2 is reduced at both the D0 and D1 stages.

Combining novel measurement technology of real time bleach load and brightness at optimum locations combined with implementation of MPC for bleach plant optimization thus has a potential to optimize bleach plant operations by

- Maintaining process parameters close to target / range
- System "automatically" takes corrective action when variability(s) is introduced
- Maintaining target pulp quality all the time – ability to shift gears dynamically
- Achieve optimum brightness range at lowest possible costs
- Dynamic modelling accounts for all variabilities including production rate changes
- Downgrades "operator interference" to minimum
- Eliminates any pulp quality issues

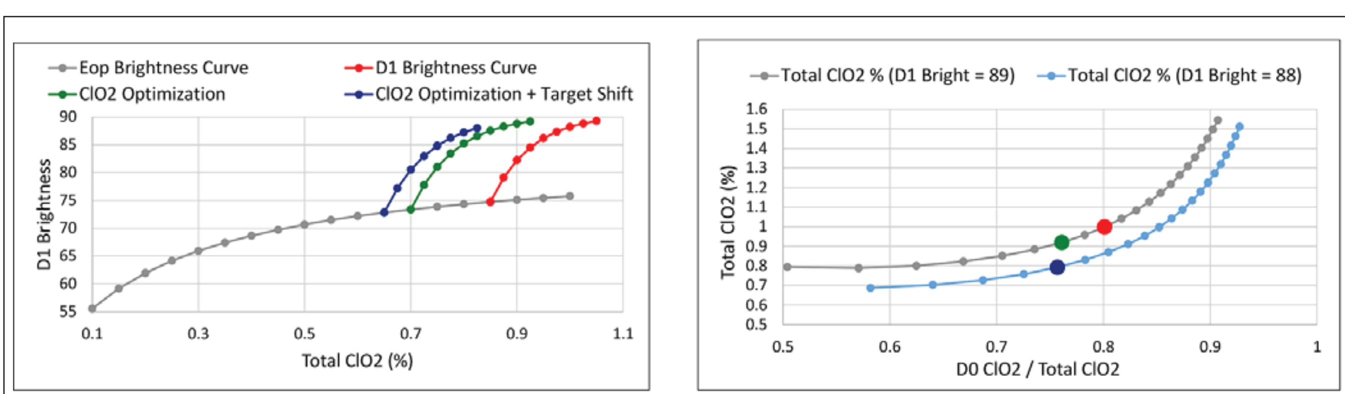

Figure 16. Bleach plant ClO_2 optimization

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Case History - Total Kappa Case History 1:

Process Description: SW bleach plant 2000 T/day with bleaching sequence $D0E_{OP}D1D2$

- Challenges:
- Bleach plant in manual control
- High chemical cost
- Quality variation / off grade

Solution:

Install Bleach Load Transmitter (Total kappa measurement) at D0 with Model Predictive Control

Results:

- Continuous bleach load measurement
- Reduced D0 chlorine dioxide by 6.3%
- Reduced sodium hydroxide usage by 7.5%
- Reduced D1 chlorine dioxide by 8%
- Reduced overall bleaching cost by 7%

Case History - Total Kappa Case History 2:

Challenges:

- Bleach Plant in manual mode
- High chemical costs
- Off grade due to brightness

Solution:

Install Bleach Load Transmitter (Total kappa measurement) at D0 with Model Predictive Control

Results:

- Continuous bleach load measurement
- Reduced D0 chlorine dioxide by 8.1%
- Reduced Eop sodium hydroxide usage by 8.8% & Eop peroxide by 20%
- Reduced D1 chlorine dioxide by 6.7%
- Increased D2 brightness from 87.1 to 90.1 on average
- Project payback was less than 1 month

CONCLUSIONS

Traditional bleach plant operation based on multi-point fiber kappa measurement combined with inline brightness and residual transmitters suffers from complex control, high operator dependence, higher chemical costs and brightness variability.

Novel single point inline total kappa (bleach load) measurement utilization has simplified chemical charge control with proven reduction in bleaching chemical costs and lowest cost of ownership (Installation, operation and maintenance costs).

Even with a solid foundation of regulatory measurements, regulatory control, and pulp quality analysers, it is practically impossible for even the best operators to manually operate a bleach plant while optimizing bleaching chemicals for pulp quality and costs.

Model predictive control (MPC) like MACS is a proven "hands-down" approach for bleach plant optimization and offers the major benefits of operating close to targets all the time, minimizing upsets, and achieving production at lowest possible costs.

Bleach load combined with MPC is a proven, powerful and simple solution for pulp makers to operate continuously within target quality and costs all the time. ■

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