Improved Model for Brightness Optimization Control in the First (C95/D5) Bleaching Stage

Xiangyu Zhang, Jigeng Li,* and Huanbin Liu

In the first stage of pulp bleaching, the quantity of added chemicals (ClO_2 and/or Cl_2) is commonly controlled by kappa factor, based on a kappa number online analyzer together with a compensated brightness control scheme as a feedback strategy. However, a kappa number analyzer is not always available, so the bleaching quality relies heavily on the chemical dosage set-point chosen by the operators. In this study, an improved model for the chlorination stage brightness optimization was proposed, based on brightness and residual chemicals before pulp enters the bleaching tower. Additionally, the experience of operators of (C95/D5) bleaching was employed in order to find an optimum chemical dosage set-point quickly. The golden section search algorithm (*i.e.*, '0.618 method') was used to find the optimum chemical dosage in this paper. After applying the proposed method in a pulp mill (C95/D5) bleaching stage, the chlorination stage brightness shifted from 62.9% ISO to the target value 60.7% ISO. Meanwhile, the standard deviation was reduced from 3.0 to 2.5.

Keywords: Kraft pulp; Bleaching; Brightness; Optimization model; Variance reduction

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INTRODUCTION

The main objective of pulp bleaching is to increase pulp brightness within specified limits. Chemical agents are applied in sequential stages to achieve the correct brightness (Flisberg *et al.* 2009). Bleach sequences vary widely from mill to mill, but the first stage is commonly the chlorine dioxide delignification (D_0) or chlorination (C or (C95D5)) stage; chlorine is still permitted for bleaching in a few regions in China. In the (C95D5) stage, unbleached or oxygen-delignified pulp is treated with chlorine (Cl_2) and chlorine dioxide (ClO_2) to decrease the kappa number (lignin content). The necessary chemical dosage depends on the incoming pulp's lignin content.

Kinetic models of chlorine dioxide (D_0), chlorine dioxide substitution ((CD)), and chlorination (C) have been researched. In the D_0 stage, a very fast delignification reaction occurs, followed by a slow one (Savoie and Tessier 1997). Likewise, the pulp brightness increases quickly during the first few minutes and then increases more slowly. Ackert *et al.* (1975) developed a model for chlorination that divides lignin into three types: fast lignin, slow lignin, and floor lignin. When the contents of fast, slow, and floor lignin are each expressed as a kappa number, the initial kappa number is equal to their sum (Ackert *et al.* 1975). This concept was later adapted to the D_0 stage from the C stage. The model of the fast and slow lignin removal rates consists of two ordinary differential equations (Tessier and Savoie 1997; Jain *et al.* 2009), which can be used to determine the chemical charge and temperature required for achieving the desired delignification. Though the

reaction consists of two phases, the relationship between chlorine consumption and kappa number decrease is linear and independent of the incoming pulp kappa number. Additionally, the pulp brightness has a linear relationship with the kappa number after the first stage (Tessier and Savoie 2000).

To predict chemical usage, kappa number, brightness, and residuals after the first bleaching stage, empirical and semi-empirical mathematical models based on experimental and operating conditions usually have been used for dynamic simulation of the bleaching process (Wang *et al.* 1995; Savoie and Tessier 1997; Tessier and Savoie 2002; Gu and Edwards 2003; Yoon *et al.* 2004). Statistical methods, polynomial regressions, and stoichiometric calculations have been employed in the modeling process, and those models could be used for bleach plant optimizations, computer simulations, and process control (Brogdon 2012, 2013, 2014). Because of the complexity of the bleaching process and its nonlinear and time-varying characteristics, models based on identification methods and neural networks have been shown to be efficient in process control (Perala and Kirby 2001; Sbarbaro *et al.* 2002; Paiva *et al.* 2004; Rajesh and Ray 2006; Flisberg *et al.* 2009; Ferrer *et al.* 2011). In a modern bleaching plant, model-based control strategies provide an efficient way to achieve better control results where online and inline sensors are widely applied (Tessier *et al*. 2000; Mercangöz and Doyle 2006).

In the D_0 stage, a feed-forward kappa factor control with compensated brightness quick feedback from the brightness and residual sensors provides good results (Tessier *et al*. 2000). Unfortunately, not all mills can afford a kappa analyzer and the associated maintenance costs. Even if a kappa analyzer is available, the kappa factor control may not follow the variance of kappa number in the sampling period (about 20 min). In this paper, a model for optimizing the chemical dosage in the (C95/D5) stage is presented. The model is based on the brightness and residual values provided by online instruments. These two values were obtained before the pulp entering into the chlorine tower. When the model was applied, it could reduce the variance of brightness after chlorination stage and shift its targets.

EXPERIMENTAL

C95/D5 Stage Bleaching Process Description

The focus of this paper was the (C95/D5) stage of a eucalypt kraft pulp mill. Its bleaching sequence was O-(C95/D5)-(EOP)-D; the (C95/D5) bleaching process is simplified in Fig. 1.

After washing, the oxygen-delignified pulp was conveyed into the brown stock tower and diluted to a suitable consistency. The control system for the first stage included local feedback loops for consistency and flow rate control. The stock consistency and flow rate could be controlled steadily and maintained at a target production rate. The pulp consistency was 2.8%, and the flow rate was 8.6 m^3/min during this process. The diluted pulp was then pumped into the mixer and mixed with the chemicals ClO_2 and Cl_2. Their ratio was 5% to 95%, respectively, and the ClO_2 solution had a concentration of 7.4 g/L. The mixed pulp was continually pumped into the (C95/D5) bleaching tower, which was an up-flow tower. The length of time that the pulp stayed in the tower depended on the production rate, but was generally approximately 30 min. The bleaching reaction started when the pulp mixed with the chemicals and was nearly completed when the pulp overflowed from the bleaching tower.

The kappa number $K_{off\text{-}line}$ after the oxygen delignification stage (O stage) was controlled to a target of 11 to 12 in an ideal situation and tested in a lab every 2 h. However, the kappa number $K_{off\text{-}line}$ was often in excess of the specified value range and brought fluctuations of the applied dosage of bleaching chemicals. The residual alkali in pulp (the percent of residual alkali in 100 gram pulp) after the oxygen delignification stage is a disturbance for kappa factor control methods in the first bleaching stage. In this bleaching process, the residual alkali ranged from 0.36% to 0.40% after the oxygen delignification (O) stage in the pulp washer. The brightness after chlorination stage $B_{off\text{-}line}$ was tested in a lab every 2 hours, and the desired brightness was 60% ISO, corresponding to the desired incoming kappa number of 11 to 12. If the initial kappa number was not the desired value, then controlling the chlorination stage brightness to the target value of 60% ISO is difficult. The bleaching temperature in the tower was maintained at 56 ºC. The online brightness analyzer (BI) and residual sensor (RI) were added before pulp entered the bleaching tower. The sampling time for brightness (b) and residual (r) in the DCS system was every 6 sec.

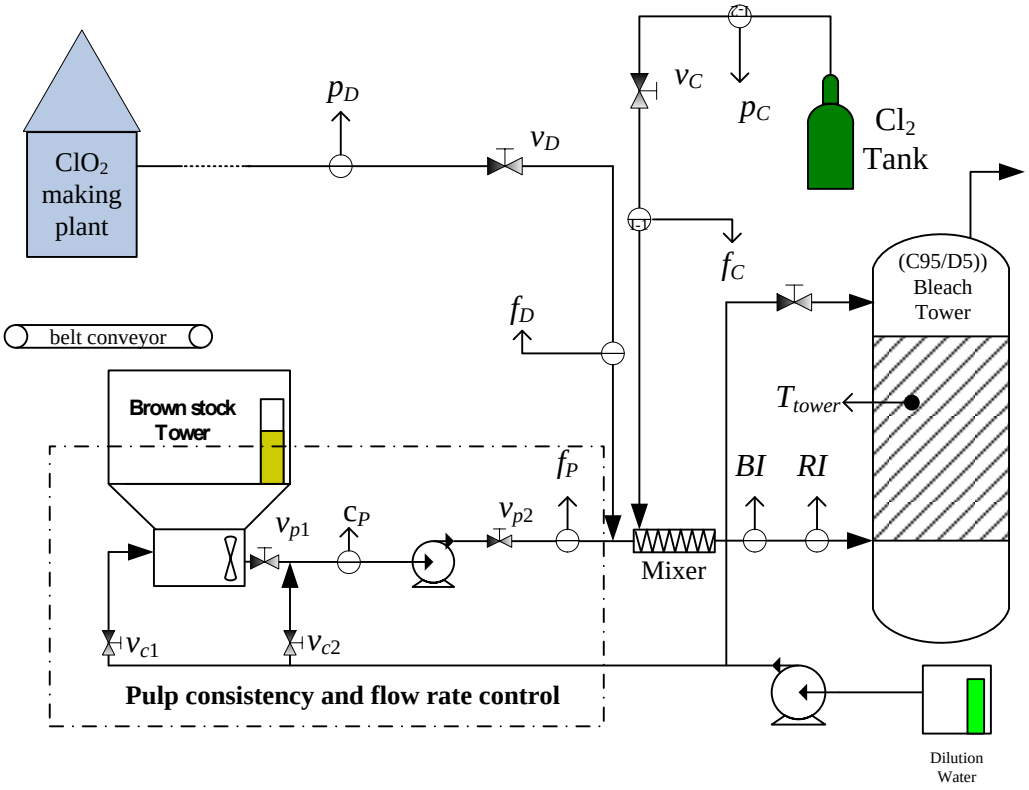

Fig. 1. Schematic diagram of the (C95/D5) bleaching stage

Generalization of a Human-supervised, DCS-based Process

The purpose of the bleaching stage (C95/D5) is to decrease the kappa number. The variation of kappa number is the main disturbance in the (C95/D5) stage. If the kappa number analyzer is available, the kappa number together with online brightness and residual provided both feed forward and feedback measurements for improved control (Tessier *et al.* 2000). If not, the compensated brightness control method was beneficial all by itself. As early as 1975, a control strategy based on a dual oxidation reduction potential ORP probes (one was mounted on before brown stock entering into bleach tower and another was on the outlet line after bleach tower) was applied in a bleach plant (Danforth

et al. 1975). The sensor after the tower gives information on how well the chlorination stage is functioning, but due to the long delay, it is not adequate for feedback control. Afterwards, sensors are also located between the mixer and the tower or at the bottom of the tower (Rankin and Bialkowski 1984; Corbi *et al.* 1986; Dumont *et al.* 1989).

Generally, when the ORP sensors were applied in the chlorination stage, the control strategies was the chlorine flow which was adjusted by a PID controller for regulating the pre-tower ORP sensors value (Cl_2 residual) to the input residual set point. The second ORP probe was used to measure the chlorine residual for feedback control and to provide information needed to adjust the pre-tower residual set point. The residual set point could be adjusted as a function of the unbleached pulp kappa number. However, if kappa number is not obtained easily, it would usually be adjusted by operators based on their experience (Danforth *et al.* 1975; Dumont *et al.* 1989; Diaz *et al.* 1992).

Because an optical sensor could be applied to measure pulp brightness, a combination of residual and brightness signals as a weighted sum, what has become known as the 'compensated brightness' signal, and is most commonly adopted in first bleaching stage. Compensated brightness control regulates the dosage of the chlorine mixture to achieve target brightness after a one minute reaction time, leaving a residual amount of chemical to complete the reaction in the bleaching tower. The total applied chemical is used with a regression model for the calculation (Rankin and Bialkowski 1984; Corbi *et al.* 1986; Cunningham 1993). The compensated brightness value is often fed to a conventional PI controller to maintain a constant brightness, which in turns cascades down to either the chlorine and or the chlorine dioxide flow controller (Van Fleet 1998), as shown in Fig. 2.

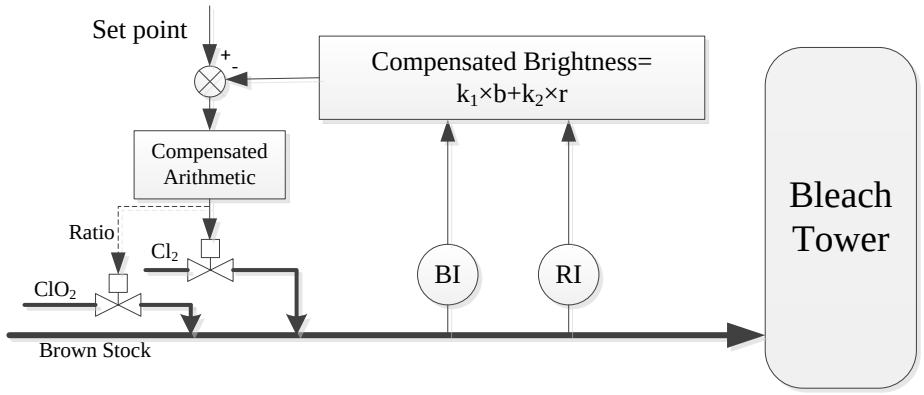

Fig. 2. Flow sheet for compensated brightness control

The essential aspect of the compensated brightness control is how to adjust the target brightness set point, which could be determined by pulp brightness after tower and/or reset by a feed-forward model for predicting incoming brown stock kappa number (Rankin and Bialkowski 1984; Corbi *et al.* 1986; Cunningham 1993). Typically, the set point has been determined from the operators' comprehensive on the process behavior (Lampela *et al.* 1996).

In the (C95/D5) stage, in order to compensate for incoming kappa number swings and other possible disturbances, besides the compensated brightness control strategy, operators often have been required to determine the proper set-point values in terms of ClO_2 flow, Cl_2 flow, and sometimes pulp flow to maintain satisfactory performance, based on various experiments and their own expertise, as shown in Fig. 3.

The supervisory control process can be described as follows: when the incoming

kappa number is changed, the disturbance ΔK causes a variation of brightness (*b*) and residual (*r*). The two values *b* and *r* were measured by Metso Kajaani CORMECS brightness analyzer and Kajaani POLAROXS chemical concentration measurement sensor (Metso Automation Inc., Finland), respectively. The operators can determine the deviation of *b* and *r* from the optimum values corresponding to current process conditions. Then, they are able to regulate the chemical flow set-point to meet the changed process conditions, according to their experience.

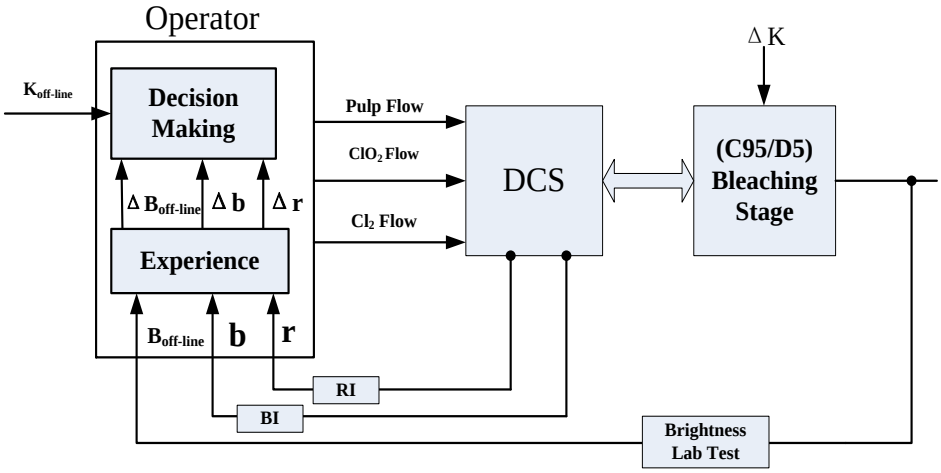

Fig. 3. Human-supervised, DCS-controlled (C95/D5) bleaching process

The operators were able to evaluate the previous regulated lab-tested values $K_{\text{off-line}}$ and $B_{\text{off-line}}$, which also played an important role in enhancing their skills and experience, increasing operator confidence of maintaining satisfactory performance.

Either compensated brightness alone or along with human supervision, the core way to regulate the applied chemicals is based on the assumption that a lower pre-tower brightness with a higher residual will eventually react with the pulp to produce a higher brightness after being discharged from the tower. Ultimately, the optimum process condition is one in which off-quality pulp is not produced and chemical is not over-applied.

Definition of Optimum Process Conditions

In (C95/D5) bleaching stage, the kinetics of chlorine bleaching with low chlorine dioxide substitution are assumed to be the same as with chlorine bleaching (Wang *et al.* 1995). Ackert *et al.* (1975) proposed a kinetic model of lignin reaction with Cl_2. It was assumed that the two first-order reactions are taking place in parallel and was described by the following equations (Eqs. l through 4), where $K_{C,f}$ and $K_{C,s}$ denote the content of fast- and slow-reacting lignin expressed as a kappa number, $[Cl_2]$ denotes the concentration of chlorine (mol/L), and $R_{C,f}$ and $R_{C,s}$ denote the rates of the fast and slow lignin removal,

$$R_{C,f} = -\frac{dK_{C,f}}{dt} = k_{C,f} * [Cl_2] * K_{C,f} \quad (1)$$

$$R_{C,s} = -\frac{dK_{C,s}}{dt} = k_{C,s} * [Cl_2] * K_{C,s} \quad (2)$$

where the reaction rate constants $k_{C,f}$ and $k_{C,s}$ are expressed as (Wang *et al.* 1995):

$$k_{C,f} = 1{,}123 * \exp(-\frac{250}{T}) \quad (3)$$

$$k_{C,s} = 22.47 * \exp(-\frac{250}{T}) \quad (4)$$

It was obvious that the rate of the fast lignin removal was much faster than that of the slow lignin, according to $k_{C,f}$ and $k_{C,s}$, where $k_{C,f}$ was more than 50 times higher than $k_{C,s}$. The fast lignin reaction could be completed in 1 to 2 min. As all of the fast lignin and slow lignin would have been removed, the delignification reaction was completed in the first bleaching stage. The remaining unreactive lignin was linked to what is known as floor lignin.

The kappa number K_C is a summation of $K_{C,f}$, $K_{C,s}$, and $K_{C,\infty}$ associated with the contents of fast, slow, and floor lignin, where $K_{C,\infty}$ is the content of floor lignin. The initial values of $K_{C,f}$, $K_{C,s}$, and $K_{C,\infty}$ are in proportion to the initial kappa number $K_{C,0}$. The proportionality coefficients were α, β, and γ, and their relationship and values were given as following equations (Eq. 5 and 6).

$$K_{C,0} = K_{C,f_0} + K_{C,s_0} + K_{C,\infty} = \alpha K_{C,0} + \beta K_{C,0} + \gamma K_{C,0} \quad (5)$$

$$\alpha = 0.5 \quad \beta = 0.3 \quad \gamma = 0.2 \quad (6)$$

In the (C95/D5) stage, the brightness and residual sensors were placed as far after the chemical injection point as possible, before the entrance of the tower. The flow rate was usually constant, so that the movement from the chemicals and pulp mixer to the instrument location took a certain amount of time (about two minutes in the studied process). It could be deduced that the fast lignin reaction was completed in a few seconds when the chemicals were mixed with pulp and that most of the slow lignin reaction had also been completed before entering the tower. Therefore, when a certain quantity of chemical agents controlled by kappa factor was added to the incoming pulp at a given kappa number, there were corresponding brightness and residual values. Those two values varied with the incoming kappa number.

To ensure that the slow lignin was removed and to avoid brightness reversion (Tessier and Savoie 2002), the residual value should be kept in proportion to the content of remaining slow lignin (Eq. 7),

$$r \propto K_s^* = (\beta K_0)^* \quad (7)$$

where K_s^* is the content of the remaining slow lignin expressed as the kappa number.

As described in the Kubelka-Munk equation, the pulp brightness is dependent on the amount of chromophoric groups in the pulp (Brogdon 2014). Lignin is the major contributor to chromophores (Tessier and Savoie 2002). The brightness before the pulp enters the tower and can display the extent of the decrease in kappa number and could also be considered an indicator of the content of unreacted slow lignin and unreactive floor lignin (Eq. 8).

$$b \propto \frac{1}{K_s^* + K_\infty} = \frac{1}{(\beta K_0)^* + \gamma K_0} \quad (8)$$

In this case, without considering temperature and final pH (because there was Cl_2 in the reaction and pH could be controlled to the desired value), the brightness *b* and residual *r*, together with the amount of total equivalent chlorine per ton of air-dried pulp provided information about the incoming kappa number, the unreactive floor lignin, and the remaining portion of slow lignin.

Field data pre-process and analysis

The primary objective for the first bleaching stage is delignification, which is achieved through oxidation of lignin in the pulp. The subsequent alkaline extraction stage (second stage) continues to remove the chlorinated organics produced in the first stage after second stage washer, where a CEK number (the kappa number after the (EOP) stage) was tested for estimating delignification in the first stage. The control strategy used for the close association two stages was to adjust the total equivalent chlorine set point to maintain a constant CEK number.

Based on the target, the evaluation of the first stage control performance is whether the brightness after chlorination stage ($B_{off\text{-}line}$) and *CEK* number were all in the specified limits. If $B_{off\text{-}line}$ and *CEK* were good value, the corresponding total equivalent chlorine *Q* was taken as the optimum value (*Q-bar*) to the unbleached pulp kappa number (*K*).

In the (C95/D5) stage, the sampling locations were the inlet before the mixer and the outlet of the up-flow chlorination tower. These locations were used to test the pulp properties of kappa number ($K_{off\text{-}line}$) and post-tower chlorination brightness ($B_{off\text{-}line}$). After the (EOP) stage, a *CEK* number was also tested.

There was a time lag when pulp flowed in the pipeline and chlorination tower. It is very important to track changes in pulp properties, and the pulp tracking method proposed by Rankin and Bialkowski (1984) was employed in this study. After coordinating the values for $K_{off\text{-}line}$ and $B_{off\text{-}line}$ with the online sensor values, human-supervised control data over a two-month period were collected from a database in the DCS system. To eliminate the noise peak jump, lower amplitude, and higher frequency noise, a digital filtering technique was employed to preprocess the original data.

In daily reports filed by operators there were 12 $K_{off\text{-}line}$ values, 12 $B_{off\text{-}line}$ values, and 12 *CEK* numbers tested in a lab every day. Control performance was evaluated based on CEK and $B_{off\text{-}line}$ data. If their values all were in the specified limits, they would be chosen as the baseline to look up their corresponding pulp flow, consistency, chemical addition quantity, and online sensor values (brightness and residual). The found homologous data was considered as a set of optimum data.

The two months of addressed data were taken as the optimum data group. The data of each group were composed of $K_{off\text{-}line}$, optimum quantity of total equivalent chlorine per ton air-dried pulp (*Q-bar*), the corresponding online brightness (*b-bar*), and online residual (*r-bar*). All the data were generated at the normal production conditions (including production rate, pulp consistency, and chlorination temperature and residence time) which have been given in the C95/D5 Stage Bleaching Process Description in EXPERIMENTAL. After having been classified and statistically analyzed, the data are summarized in Table 1. To illustrate the relationship between different kappa number and optimum quantity of total equivalent chlorine per ton air-dried pulp (*Q-bar*), the corresponding online brightness (*b-bar*), the group data were plotted in a scatter diagram, which suggested there were almost linearly relationships between *Q-bar* ($\bar{Q}$) and *b-bar* ($\bar{b}$) with *K*. Besides, one online

brightness come pair with one residual, and the relationship of corresponding *r-bar* ($\bar{r}$) with *b-bar* ($\bar{b}$) was also approximately linear, as shown in Fig. 4.

Table 1. Kappa Number and Corresponding Optimum Process Variables Values

$K_{off\text{-}line}$	7.8	8.6	9.5	10.2	11.0	12.3	13.4	14.3	15.3
Q-bar (kg/ton a.d.p)	15.2	16.5	17.3	18.7	20.6	23.5	25.1	27.9	30.3
b-bar (%ISO)	59.1	58.3	57.6	56.3	55.0	54.6	53.0	51.8	50.0
r-bar (mg/l)	8.5	9.3	14.6	18.6	22.7	29.5	35.2	38.6	47.9
$B_{off\text{-}line}$ (%ISO)	62.3	62.0	61.5	61.0	60.2	59.8	58.7	58.1	57.2
CEK number	0.8	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.3

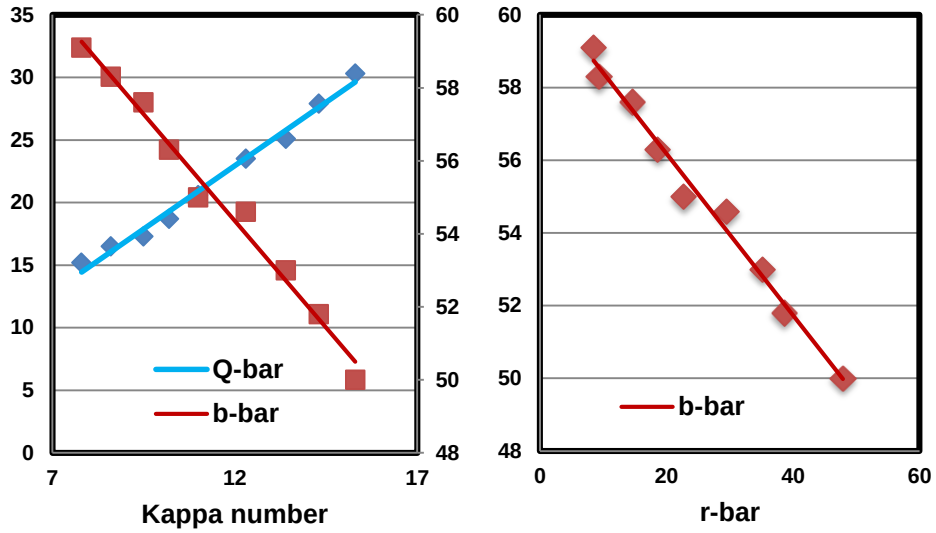

Fig. 4. The relationship of *Q-bar* and *b-bar* with unbleached pulp kappa number (left); relationship of *r-bar* with *b-bar* (right)

Optimum process conditions

When diluted pulp with different incoming kappa numbers (K) was mixed with bleaching agents (Q = the quantity of total equivalent chlorine per ton of air-dried pulp), there were different corresponding online brightness (b) and residual (r) values before the pulp entered the bleaching tower, b and r values arise in pairs.

$$\begin{cases} b = G_1(K, Q) \\ r = G_2(K, Q) \end{cases} \quad (9)$$

In equation set (9), the functions G_1 and G_2 were the real bleach process when chemical mixed with pulp in the mixer. The quantity of chemical was Q and the kappa number of incoming pulp was K.

Kappa number drop is linearly related to the chemical consumption (Savoie and Tessier 1997), and it is the main indicator of the bleaching load or chemical demand (Van Fleet 1998). Based on Fig. 4, it can be deduced that the optimum quantity *Q-bar* and the initial kappa number *K* have a linear correlation.

$$F(K, \overline{Q}) = a_1 * K + b_1 * \overline{Q} + c_1 = 0 \quad (10)$$

The parameters a_1, b_1, and c_1 could be determined by a least square method based on the data in Table 1.

When the applied quantity of total equivalent chlorine was its optimum value of *Q-bar*, the corresponding brightness and residual would be an optimum pair *b-bar* and *r-bar*.

$$\begin{cases} \overline{b} = G_1(K, \overline{Q}) \\ \overline{r} = G_2(K, \overline{Q}) \end{cases} \quad (11)$$

When $\overline{Q} = -\frac{1}{b_1}(a_1 * K + c_1)$ was substituted in Eq. 11, the results were:

$$\begin{cases} \overline{b} = G_1(K, F(K)) \\ \overline{r} = G_2(K, F(K)) \end{cases} \quad (12)$$

Equation 12 could be simplified to Eq. 13:

$$\begin{cases} \overline{b} = H_1(K) \\ \overline{r} = H_2(K) \end{cases} \quad (13)$$

According to the above analysis, it can be concluded that there was a one-to-one correspondence between the optimum pair (*b-bar* and *r-bar*) and the kappa number of incoming pulp because there was only one optimum *Q-bar* for the given kappa number pulp. The pairs continuously varied over different incoming kappa numbers.

$$\begin{cases} \overline{b} \propto \frac{1}{K} \\ \overline{r} \propto K \end{cases} \quad (14)$$

Further, there was a correlation between *b-bar* and *r-bar*, which can be reasoned out from Eq. 14. The relationship between b-bar and r-bar was approximately liner as shown in Fig. 4.

$$f(\overline{b}, \overline{r}) = a_2 * \overline{b} + b_2 * \overline{r} + c_2 = 0 \quad (15)$$

The parameters a_2, b_2, and c_2 also could be determined by a least-squares method based on the data in Table 1.

Therefore, if the online brightness and residual was an optimum pair, their value would be a solution of Eq. 15. In other words, if *b* and *r* was an optimum pair, the current condition is OPC. Furthermore, a sub-optimal pair accounted for the current *Q* and was not

an optimum value, and the current process condition was not OPC which would bring about bleaching off-grade pulp.

Although modern bleaching plants are controlled with the help of inline and online sensors using advanced control strategies, the operators' controlling experience is the key point in optimizing the economic performance and maintaining the bleaching quality. A model for process optimization was combined 'compensated brightness' and expertise operators' experience and was developed to improve product quality and reduce the operators' burdens.

Model for Process Optimization

The assumption (*b,r*) was expressed in terms of the online brightness and residual of the current condition, and *X*(*b,r*) was one point of process condition coordinate space that was made up of brightness and residual before pulp entered the bleaching tower during the bleaching process, as shown in Fig. 5.

The line $f(\bar{b},\bar{r}) = 0$ was based on the optimum pairs (*b-bar and r-bar*) of different kappa number pulp on the coordinate plane. The control's job was to regulate the *X* (*b,r*) at optimum condition $\overline{X}(\bar{b},\bar{r})$.

A line drawn that includes the initial point *X* (*b,r*) and intersected the function $f(\bar{b},\bar{r}) = 0$ at point $O_r(b_r,r_r)$. So, $f(b_r,r_r) = 0$.

Suppose that the slope of this drawn line was *k*. Then the drawn line could be expressed as follows (Eq. 16),

$$b_r - b = k(r_r - r) \tag{16}$$

because of the drawn line intersected with function $f(\bar{b},\bar{r}) = 0$, where

$$k \neq -\frac{1}{a_2}(b_2 * \bar{r} + c_2).$$

When the optimal quantity of corresponding chemicals Q_r of condition $O_r(b_r,r_r)$ was added to the current condition *X*(*b,r*), there would be a new process condition $X_r(b_r^*,r_r^*)$.

If $f(b_r^*,r_r^*) = 0$ and $b_r^* = b_r$, $r_r^* = r_r$, then the pair (b_r,r_r) was regarded as an optimum one under current process conditions, and Q_r was the optimum value.

If $f(b_r^*,r_r^*) \neq 0$ and $b_r^* \neq b_r$, $r_r^* \neq r_r$, then the pair (b_r, r_r) was not an optimum one under current process conditions, and Q_r was not the optimum value.

In fact, if the process condition $X_r(b_r^*,r_r^*)$ fell within the circle with $O_r(b_r,r_r)$ as the center point and ε as the radius, it could be taken as an optimum. If not, regulation is necessary for an OPC. The ε is a minimum acceptable tolerance to determine whether the *b* and *r* of the process condition could be accepted as optimum values. As shown in Fig. 5, Drawn Line 1 is an OPC, and Drawn Line 2 is not.

Based on the analysis, an optimization model could be established for reducing the variance of brightness after chlorination stage and its target could be shifted to a desired value, which can be applied to brightness control through regulating the quantity of added chemicals.

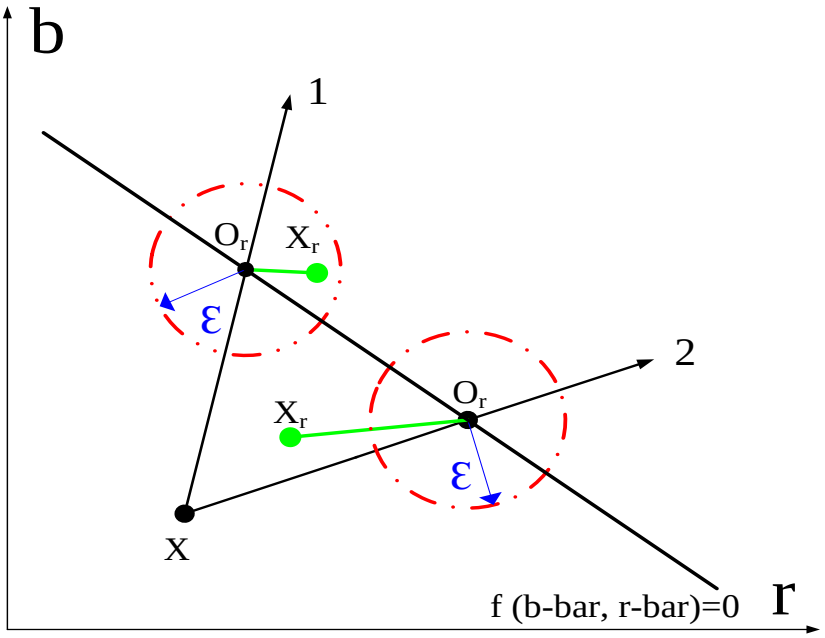

Fig. 5. Optimum process conditions in (C95/D5) bleaching process; optimization model regulates the sub-optimal condition into OPC

The distance of a quadratic relationship between $X_r(b_r^*,r_r^*)$ and $O_r(b_r,r_r)$ can be treated as an objective function subject to constraints that consist of the process models and the lower and upper limits of process variables in the (C95/D5) bleaching stage. A minimization problem was described as follow (Eq. 17),

$$\min \quad z = (b_r - b_r^*)^2 + (r_r - r_r^*)^2 \tag{17}$$

where b_r and r_r are obtained from Eq. 18 with Eq. 15 and 16:

$$\begin{cases} b_r - k * r_r + k * r - b = 0 \\ a_2 * b_r + b_2 * b_r + c_2 = 0 \end{cases} \tag{18}$$

To obtain (b_r^*,r_r^*), the corresponding optimum quantity chemicals Q_r of (b_r,r_r) should be applied in the bleaching process (Eq. 9).

The relationship of *K* and *b-bar* could be deduced from Eq. 13 and Fig. 4. A linear expression between them was as follow (Eq. 19):

$$a_3 * K + b_3 * \bar{b} + c_3 = 0 \tag{19}$$

The parameters a_3, b_3 and c_3 could be determined by a least square method based on the data in Table 1.

When b_r was substituted in Eq. 19 together with Eq. 10 as follows, the Q_r could be obtained:

$$\begin{cases} a_1 * K + b_1 * Q_r + c_1 = 0 \\ a_3 * K + b_3 * b_r + c_3 = 0 \end{cases} \tag{20}$$

After the Q_r was applied, b_r^* and r_r^* values could be obtained from the brightness analyzer (BI) and residual sensor (RI). The optimization process is to search a Q_r value until z was less than a minimum value ε^2.

The improvement provided by this model is that an appropriate minimum value ε could ensure a stabilized control performance. There is no regulation when the variations of *b* and *r* are acceptable. Besides, the model could auto-reset the set point of applied chemicals in response to variations of the unbleached pulp kappa number.

The compensated brightness control strategy is common practice in the pulp mill. However, the regulation of applied chemicals is often difficult in the optimum case. The algorithm directly assesses brightness and residual sensor signals combined using weighting factors, as shown in Fig. 2, and oscillation in the controller's output are common. What is more, the major consequence of this strategy is that the operator is forced to over-apply chemicals in order to ensure that off-quality pulp is not produced (Van Fleet 1998) through adjusting the target value set point. Thus, the compensated brightness model has been often unemployable and the DCS control mode is commonly being run on manual mode, supervised by the operator.

There was a trend of chlorine flow adjusted by the improved optimization model and human-supervised compensated brightness model, as shown in Fig. 6. The swings of chlorine flow adjustment by the compensated brightness model were frequent. The adjustment resulted in improved optimization with more stability and smoothness.

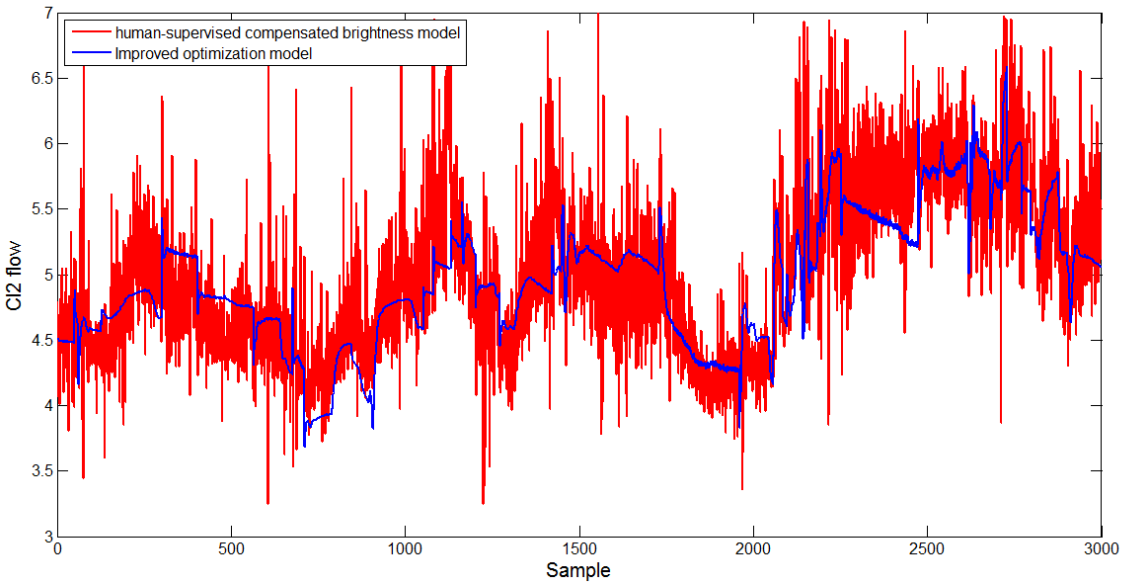

Fig. 6. The trend of chlorine flow adjusted by improved optimization model and human-supervised compensated brightness model

RESULTS AND DISCUSSION

Operating Modes in Two Different Conditions

When process conditions were sub-optimal, there were two operating modes in terms of chemical dosage (overcharged and undercharged) that reduced the chemical flow

or increased the chemical flow. Equation 15 is the relationship between optimum pair *b-bar* and *r-bar* for different initial kappa numbers when the quantity of added chemicals was optimum. If the process condition was not an optimum one, then *b* and *r* were not a solution to Eq. 15. It was possible to deduce the status of a current condition through the following rules, where *b* and *r* denote the online brightness and residual of the current process condition:

1) if $f(b,r) > 0$, chemical agent was overcharged;
2) if $f(b,r) = 0$, optimum process condition; or
3) if $f(b,r) < 0$, chemical agent was undercharged

During the bleaching process, the operators' main job is to quickly adjust or maintain process conditions at an optimum. If the current process condition is not an optimum one as shown in Fig. 7, the optimization model could be employed to solve this problem.

Where $X_r(k\text{-}1)$ denotes the current process condition after the last optimized step, $O_r(k)$ denotes the hypothetical optimal condition for the current condition and $X_r(k)$ denotes the process condition after this time optimization; $O_r(k+1)$ and $X_r(k+1)$ denote the next time optimizing step conditions, if $X_r(k)$ still does not meet requirements.

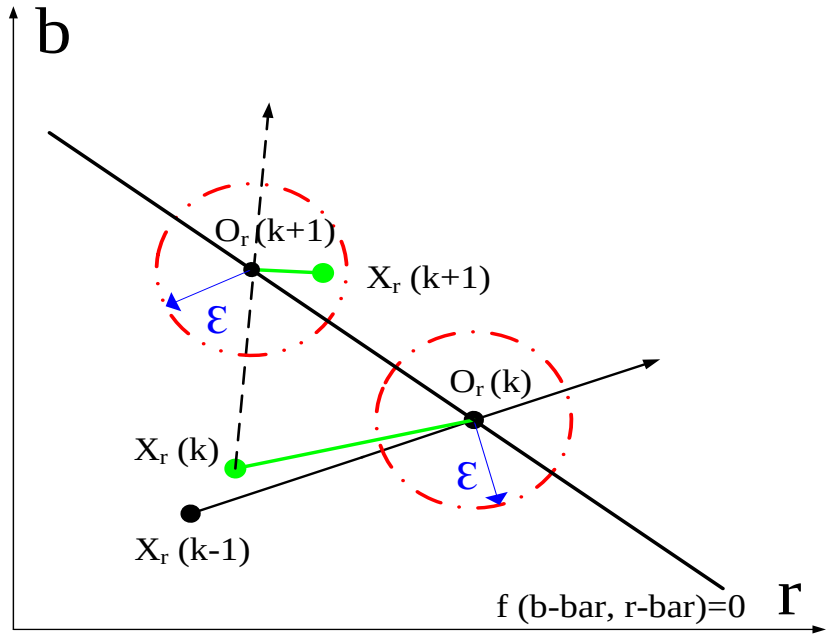

Fig. 7. Search procedure for a sub-optimal process condition in the optimization process

Given that the current pre-tower pair brightness and residual was (b_1,r_2), so the $X(b_1,r_2)$ was one point on the coordinate plane of process condition:

1) When $\bar{b}$ was substituted with b_1 in $f(\bar{b},\bar{r}) = 0$, there was a corresponding value r_1; and

2) When $\bar{r}$ was substituted with r_2 in $f(\bar{b}, \bar{r}) = 0$, there was a corresponding value b_2

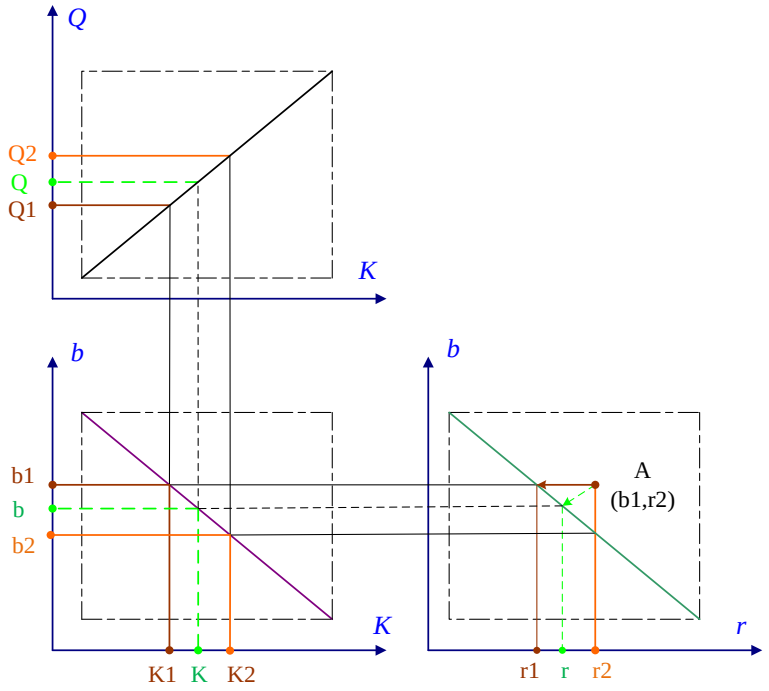

Fig. 8. Operation step of chemicals overcharged in the optimization process

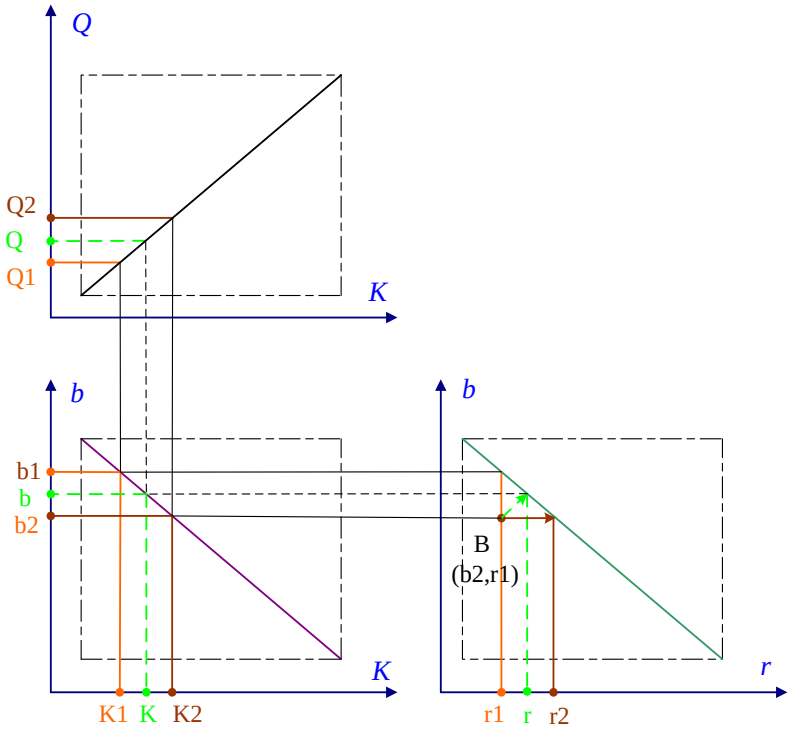

Fig. 9. Operation step of chemicals undercharged in optimization process

The OPC $(\bar{b},\bar{r})$ of current condition $X(b_1,r_2)$ must eventually be between the corresponding process conditions of $O_1(b_1,r_1)$ and $O_2(b_2,r_2)$. Namely, the optimum quantity of added chemicals $\bar{Q}$ must be between the corresponding quantity Q_{O_1} of $O_1(b_1,r_1)$ and Q_{O_2} of $O_2(b_2,r_2)$.

When the current online brightness and residual is $A(b_1,r_2)$, as shown in Fig. 8 $f(b_1,r_2) > 0$, the current chemical dosage was overcharged. The optimum Q of the current process condition must be between Q_1 and Q_2 and the optimum online brightness b and residual r also between b_1 and b_2, r_1 and r_2. The upper and lower limits can be calculated following the directions in Fig. 8 with the Eqs. 10, 15, and 19.

The method can also be adopted to optimize an undercharged chemical dosage, as shown in Fig. 9.

Method for Solving Optimization Process

After breaking the process of optimization down into two modes and three steps, the mathematical search procedure became a one-dimensional search. When the current process condition after $k\text{-}1^{th}$ optimization was $x^{(k)}(b^{(k)},r^{(k)})$, where online brightness and residual was $b^{(k)}$ and $r^{(k)}$, the golden section search algorithm (*i.e.*, '0.618 method') (Sun and Yuan 2006) was used to find out the optimum quantity of chemicals addition:

1) If $f(b^{(k)},r^{(k)}) = 0$, the current quantity of chemical addition $Q^{(k)}$ was optimal and it is not necessary to regulate the chemical flow.
2) If $f(b^{(k)},r^{(k)}) \neq 0$, each corresponding optimum pair could be obtained, *i.e.* $(b^{(k)}, r_{b^{(k)}})$ and $(b_{r^{(k)}}, r^{(k)})$, from the solution of $f(b^{(k)},r) = 0$ and $f(b,r^{(k)}) = 0$. The optimum $Q_{b^{(k)}}$ and $Q_{r^{(k)}}$ were obtained when $(b^{(k)}, r_{b^{(k)}})$ and $(b_{r^{(k)}}, r^{(k)})$ were substituted in Eqs. 10 and 19. If $f(b^{(k)},r^{(k)}) > 0$, the k^{th} ($k = 1, 2, \ldots, l$) time-searched value $Q_{0.618}{}^{(k)}$ was taken from the upper-lower limit between $[Q_{b^{(k)}}, Q_{r^{(k)}}]$. The value was equal to $Q_{r^{(k)}}$ minus 0.618 times the distance between the ranges $[Q_{b^{(k)}}, Q_{r^{(k)}}]$. When $Q_{0.618}{}^{(k)}$ was substituted in Eqs. 10 and 19, point $O_r(k)$ (*i.e.*, $(b_r^{(k)}, r_r^{(k)})$) was obtained. After $Q_{0.618}{}^{(k)}$ was substituted in Eq. 9 (the quantity of added chemicals is $Q_{0.618}{}^{(k)}$ in current bleaching process), the point $X_r(k)$ that the current process condition (*i.e.*, $(b_r^{*(k)}, r_r^{*(k)})$) after k^{th} time-searched steps could be obtained. If $f(b^{(k)},r^{(k)}) < 0$, the k^{th} ($k = 1, 2, \ldots, l$) time-searched value $Q_{0.382}{}^{(k)}$ was taken from the upper-lower limit between $[Q_{b^{(k)}}, Q_{r^{(k)}}]$. The value was equal to $Q_{b^{(k)}}$ plus 0.382 times the distance between the range $[Q_{b^{(k)}}, Q_{r^{(k)}}]$. When $Q_{0.382}{}^{(k)}$ was substituted in Eqs. 10 and 19, point $O_r(k)$ (*i.e.*, $(b_r^{(k)}, r_r^{(k)})$) was obtained. After $Q_{0.382}{}^{(k)}$ was substituted in Eq. 9 (the quantity of added chemicals was $Q_{0.382}{}^{(k)}$ in current bleaching process), the point $X_r(k)$ that the current process condition $(b_r^{*(k)}, r_r^{*(k)})$ after k^{th} time-searched steps could be obtained.
3) If $z \leq \varepsilon^2$, the value $Q_{0.618}{}^{(k)}$ (or $Q_{0.382}{}^{(k)}$) was the optimum chemical dosage. If $z > \varepsilon^2$, step 2 was repeated until $z \leq \varepsilon^2$.

Human-supervised and Optimization Model-based Results

The proposed model was programmed in a workstation computer with Siemens WinCC, and the model result was sent to the distributed control system (DCS) automatically. After applying the proposed improved optimization model in the (C95/D5) bleaching stage, the brightness after chlorination stage could be controlled around the target values. Meanwhile, the standard deviation of post-tower brightness also was reduced after shifting the target.

The chlorination stage brightness frequency distribution of pre-optimization and post-optimization are shown in Fig. 10. A month of pre-optimization brightness data was collected. The mean value of brightness was 62.9% ISO and its standard deviation was 3.0. After the proposed method was applied for a month, the brightness shifted from 62.9 to 60.7% ISO. Additionally, the standard deviation shrank to 2.5. Namely, the fluctuation of chlorination stage brightness evidently decreased while the mean value shifted.

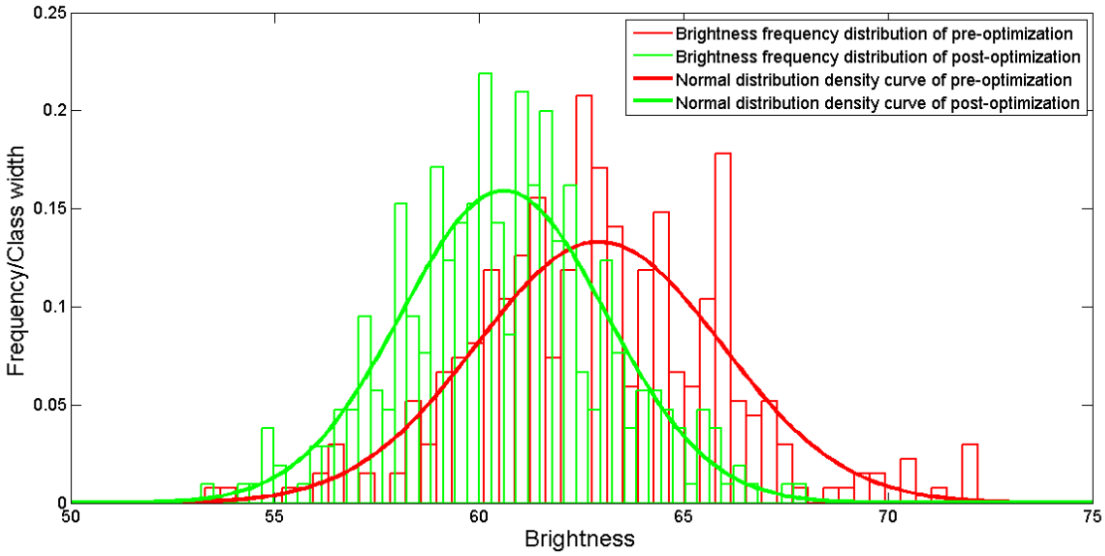

Fig. 10. The brightness after chlorination stage frequency distribution of pre-optimization and post-optimization

CONCLUSIONS

1. The brightness and residual values before the pulp entered the bleaching tower provided useful information to estimate the extent of the reaction and the incoming pulp properties. With analysis results of bleaching process data and the expert knowledge and operation experience in (C95/D5) stage, the information can be modeled as an auto-optimization model.
2. According to contrasting results, the proposed model-based optimization method can shift targets and reduce variance in the chlorination stage brightness. The proposed method can be applied to the (C95/D5) beaching stage without a kappa number analyzer, in place of an inherently inefficient human-supervised compensated brightness control process. Additionally, it can be employed in a

kappa factor control strategy as an improved brightness-compensated control feedback control scheme in the first bleaching stage.

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