Hot Chlorine Dioxide versus Conventional D_0 Stage in ECF Bleaching of Kraft Pulps

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ECF bleaching of mixtures of hardwood and bamboo pulps from paper mills was carried out in different bleaching sequences to full brightness. Kappa factor was optimized in each case to get the desired optical properties with judicious use of bleaching chemicals. Comparison between conventional ECF bleaching and the hot chlorine dioxide bleaching was done and the effects of hot D stage on the various pulp properties, chemical consumption and AOX generation were studied.

Bleachability of 80% hardwood and 20% bamboo pulp was found to be better as compared to 40% hardwood and 60% bamboo pulp in ECF sequence and it required the lowest kappa factor (0.22) to bleach to 90+ brightness levels. Kappa factor requirement for ECF bleaching of 40% hardwood and 60% bamboo pulp was 0.33. The substitution of standard D_0 stage with D_{HT} stage in conventional ECF bleaching reduced HexA content and improved the brightness and other optical properties. D_{HT} stage also reduced the chlorine dioxide consumption, which resulted in reduced generation of AOX. It was possible to achieve AOX level < 1.0 kg/TP in case of 40% hardwood and 60% bamboo pulp and 0.5 kg/TP in case of 80% hardwood and 20% bamboo pulp when bleached in $D_{HT}E_{OP}D_1D_2$, $D_{HT}E_{OP}D_1ED_2$, $D_{HT}E_{OP}D_1P$ and $D_{HT}E_{OP}PD_1$ sequences without using oxygen delignification.

INTRODUCTION

Increasing awareness about environmental concerns has led the paper industry to look for cleaner production options aimed at the reduced consumption of chlorine and its compounds in the bleaching sequences which thereby minimizes the discharge of organochlorine compounds in the effluent, AOX (1). These organo-chlorine compounds are produced mainly by the reactions between residual lignin present in the wood fibers and the chlorine used for bleaching. Some of these compounds are found to be toxic, mutagenic, persistent, bioaccumulating, and harmful to biological systems (2).

Elemental chlorine-free (ECF) bleaching for the pulp and paper industry, based on chlorine dioxide, offers a number of fundamental benefits over the traditional methods. The U.S. EPA's Cluster Rule for the pulp and paper industry has ECF as one of its core Best Available Technology (BAT) elements (3). In addition to producing the highest pulp quality, ECF bleaching has proven itself to be a pollution prevention process for the pulp and paper industry. Perhaps most important is the fact that the use of chlorine dioxide in the first stage of chemical pulp bleaching virtually eliminates dioxins and 12 priority chlorophenols proposed by the U.S. Environmental Protection Agency (EPA) for regulation to non-detect levels. The other benefits of ECF bleaching are that it decreases chloroform formation and total chlorinated organic compound (AOX) formation by 90%; efficiently utilizes forest resources; contributes to eco-system recovery; and is compatible with emerging minimum-impact mill technologies (3).

Several studies (4-5) have shown that incorporation of hot chlorine dioxide stage in ECF bleaching helps in reducing the ClO_2 consumption and have a positive impact on the brightness stability of bleached pulps. Eiras and Colodette (4) investigated the effect of hot D stage (D_{HT}) on the bleaching of an industrial oxygen delignified kraft pulp of kappa number 8.7 comparing D_0EopD and D_{HT}EopD sequences. The standard initial D stage (D_0) was performed at 60°C for 30 minutes, whereas the D_{HT} stage was performed at 95°C for 180 minutes. Hexenuronic acid (HexA) content was found to decrease from 57.2 to 16.3 and 13.3 mmol/kg for the D_0EopD and D_{HT}EopD sequences respectively. They found that the D_{HT}EopD sequence consumed 11% less ClO_2 with improved brightness stability. It also resulted in reduction of AOX content of the filtrate and lower AOX content of the bleached pulp by 36% and 13% respectively.

In the present study, ECF bleaching of 80% hardwood and 20% bamboo pulp and 40% hardwood and 60% bamboo pulp was carried out in different bleaching sequences to full brightness. Kappa factor was optimized in each case to get the desired optical properties with judicious use of bleaching

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chemicals. Comparison between conventional ECF bleaching and the hot chlorine dioxide bleaching was also done and the effect of hot D stage on the various pulp properties, chemical consumption and AOX generation was studied. This study will help find an amicable solution to ever increasing environmental pressure to reduce the generation of organochlorine compounds (AOX) in the bleach plant effluents.

EXPERIMENTAL

Unbleached plant pulps from different mills containing 80% hardwood and 20% bamboo pulp (Kappa no. of ~ 18.0) and 40% hardwood and 60% bamboo pulp (Kappa no. of ~ 20.0) were bleached in different ECF sequences using ClO_2. The bleaching conditions are given in the corresponding tables. Pulps were also treated with chlorine dioxide at 85 °C for 120 min in the initial stage (D_{HT}) and compared with standard D_0 stage performed at 55°C for 30 minutes. Bleached pulps were characterized for brightness, CIE whiteness, L*a*b* values, yellowness, post colour (PC) number and viscosity. Bleaching effluents were analyzed for AOX.

Analytical techniques

Moisture content of pulp was determined as per Tappi Test Method T 210 cm-86.

Brightness and whiteness of pulp were determined using Technibrite Brightness Meter (Model TB 1c) as per Tappi Test Method T 525 om-02 and T560 pm-96 respectively.

Whiteness of pulp was determined using Spectraflash 300 UV (Datacolor, USA) as per Tappi Test Method T560 pm-96.

PC No. of pulp was determined as per Tappi Test Method T 260 om-85

HexA content was determined using HUT method (6).

Viscosity, of pulp was measured as per Tappi Test Method T 230 om-82.

AOX was determined as per ISO method No. 9562:1989 using Euroglass B.V., Netherlands AOX analyser (Model ECS 2000).

Kappa factor optimization

Chlorine dioxide dose in D_o stage of $D_oEopD_1D_2$ and D_oEopD_1P bleaching sequences was optimized by using 0.20-0.35 kappa factors. It was observed that kappa factor 0.33 in $D_oEopD_1D_2$ sequence and 0.30 in D_oEopD_1P sequence resulted in achieving the required final optical properties (Table 1).

ECF bleaching in different sequences

ECF bleaching of 40% hardwoods and 60% bamboo pulp was carried out by using $D_oEopD_1D_2$, D_oEopD_1P, $OD_oEopD_1D_2$, OD_oEopD_1P, $O_1O_2D_oEopD_1D_2$ and $O_1O_2D_oEopD_1P$ sequences. Brightness, whiteness, brightness stability were better and AOX generation was lower in case of D_oEopD_1P sequence as compared to $D_0EopD_1D_2$ sequence (Table 2). These results are in agreement with the findings of French researchers (7) who reported that use of peroxide in the end of the bleaching sequence results in better brightness and whiteness. Peroxide is one of the best candidates for degrading quinines, which are mainly responsible for yellowing of the pulp. Use of ClO_2 actually leads to slow

Table 1: ECF Bleaching of 40% hardwood and 60% bamboo pulp in $D_oE_{OP}D_1D_2$ and $D_oE_{OP}D_1P$ sequences at varying kappa factors Comparison of bleached pulp properties & bleach chemical requirements

Bleaching sequence	Kappa factor	Brightness (% ISO)	CIE whiteness	PC no.	Viscosity (cp)	Bleached yield (%)	NaOH (kg/TP)	H_2O_2 (kg/TP)	ClO_2 (kg/TP)
$D_oE_{OP}D_1D_2$	0.20	84.6	74.5	0.43	14.7	94.4	18.0	5.0	26.4
	0.22	84.9	74.9	0.45	14.6	93.7	18.0	5.0	27.9
	0.25	85.9	76.6	0.47	14.4	93.7	18.0	5.0	30.1
	0.30	87.3	79.1	0.46	14.4	93.5	18.0	5.0	33.7
	0.33	89.1	82.6	0.42	14.1	93.4	18.0	5.0	35.8
	0.35	89.4	83.9	0.40	14.1	93.4	18.0	5.0	37.3
$D_oE_{OP}D_1P$	0.20	86.7	80.5	0.34	14.7	94.9	24.7	10.0	22.4
	0.22	87.4	81.1	0.38	14.1	94.5	24.7	10.0	23.9
	0.25	88.2	82.8	0.38	13.9	94.0	24.7	10.0	26.1
	0.30	89.6	83.7	0.35	14.4	94.0	24.7	10.0	30.0
	0.33	89.8	83.9	0.33	14.3	94.0	24.7	10.0	31.8
	0.35	89.9	84.4	0.32	14.3	93.7	24.7	10.0	33.3

RESULTS AND DISCUSSION

A. 40% hardwood and 60% bamboo pulp

Table 2: ECF Bleaching of 40% hardwood and 60% bamboo pulp in different bleaching sequences Comparison of bleached pulp properties, bleach chemical requirements and AOX generation

Bleaching sequence	Brightness (% ISO)	CIE whiteness	PC no.	Bleached yield (%)	Viscosity (cp)	NaOH (kg/TP)	H_2O_2 (kg/TP)	ClO_2 (kg/TP)	AOX (kg/TP)
$D_oE_{OP}D_1D_2$	89.1	82.6	0.42	93.4	14.1	18.0	5.0	35.8	**1.04**
$D_oE_{OP}D_1P$	89.6	83.7	0.35	94.0	14.4	24.0	10.0	30.0	**0.77**
$O_1D_oE_{OP}D_1D_2$	89.5	84.1	0.28	94.5	13.2	10.0	5.0	23.8	**0.57**
$O_1D_oE_{OP}D_1P$	89.8	84.4	0.18	94.6	13.6	14.4	8.0	21.8	**0.44**
$O_1O_2D_oE_{OP}D_1D_2$	89.8	84.5	0.16	94.2	12.1	10.0	5.0	21.3	**0.33**
$O_1O_2D_oE_{OP}D_1P$	89.9	84.7	0.13	94.1	12.2	14.4	8.0	19.3	**0.28**

Table 3: Effect of hot chlorine dioxide in ECF bleaching of 40% hardwood and 60% bamboo pulp *Comparison of bleached pulp properties, bleach chemical consumption and AOX generation*

Bleaching sequence	**Brightness (% ISO)**	**CIE whiteness**	**PC no.**	**Bleached yield (%)**	**Viscosity (cp)**	**HexA in bld. pulp (mmol/kg)**	**NaOH (kg/TP)**	**H_2O_2 (kg/TP)**	**ClO_2 (kg/TP)**	**AOX (kg/TP)**
$D_oE_{OP}D_1D_2$	89.1	82.6	0.42	93.4	14.1	1.90	18.0	5.0	35.8	1.04
$D_{HT}E_{OP}D_1D_2$	89.5	83.7	0.38	93.5	13.9	1.40	18.0	5.0	30.7	0.80
$D_oE_{OP}D_1P$	89.6	83.7	0.35	94.0	14.4	1.93	24.0	10.0	30.0	0.77
$D_{HT}E_{OP}D_1P$	89.8	84.8	0.27	94.3	14.2	1.35	24.0	10.0	25.0	0.67
$OD_oE_{OP}D_1D_2$	89.5	84.1	0.28	94.5	13.2	1.70	10.0	5.0	23.8	0.57
$OD_{HT}E_{OP}D_1D_2$	89.7	85.3	0.22	94.8	13.0	1.40	10.0	5.0	21.0	0.43
$OD_oE_{OP}D_1P$	89.8	84.4	0.18	94.6	13.6	1.75	14.4	8.0	21.8	0.44
$OD_{HT}E_{OP}D_1P$	90.0	85.6	0.13	94.8	13.3	1.42	14.4	8.0	19.0	0.40
$O_1O_2D_oE_{OP}D_1D_2$	89.8	84.5	0.16	94.2	12.1	1.50	10.0	5.0	21.3	0.33
$O_1O_2D_{HT}E_{OP}D_1D_2$	90.1	85.6	0.10	94.7	11.9	1.20	10.0	5.0	19.0	0.25
$O_1O_2D_oE_{OP}D_1P$	89.9	84.7	0.13	94.1	12.2	1.55	14.4	8.0	19.3	0.32
$O_1O_2D_{HT}E_{OP}D_1P$	90.0	85.7	0.08	94.3	11.9	1.28	14.4	8.0	17.0	0.29

and incomplete destruction of quinonic chromophores and also creation of new quinone groups (7). Therefore, use of dioxide in the end of the bleaching sequence is not the best choice in terms of brightness development. There was a considerable reduction in bleach chemical requirement when single and two-stage oxygen delignification were incorporated before $D_oEopD_1D_2$, D_oEopD_1P sequences (Table 2). Brightness and whiteness were highest and the AOX generation was lowest in $O_1O_2D_oEopD_1P$ sequence. Consumption of chlorine dioxide was also least in this sequence in comparison to other bleaching sequences. Total ClO_2 consumption was 35.8, 30.0, 23.8, 21.8, 21.3, 19.3 kg/TP in case of $D_oEopD_1D_2$, D_oEopD_1P, $OD_oEopD_1D_2$, OD_oEopD_1P, $O_1O_2D_oEopD_1D_2$ and $O_1O_2D_oEopD_1P$ bleaching sequences respectively.

Effect of hot chlorine dioxide stage in ECF bleaching

A number of bleaching sequences were studied as shown in Table 3. The standard D_o stage was performed at 55°C for 45 minutes, whereas the D_{HT} stage was performed at 85°C for 120 minutes. It was found that the $D_{HT}EopD_1D_2$ and $D_{HT}EopD_1P$ sequences consumed 14.2 % and 16.6 % less ClO_2 respectively and showed better brightness, whiteness and brightness stability when compared to reference sequences ($D_oEopD_1D_2$, D_oEopD_1P) (Table 3). It also reflects the reduction in AOX generation in their effluents in comparison to reference sequences and reduction in the HexA content in the final bleached pulps by hot chlorine dioxide treatment.

When the conventional ECF bleaching sequences including single and double stage oxygen delignification ($OD_oEopD_1D_2$, OD_oEopD_1P, $O_1O_2D_oEopD_1D_2$, $O_1O_2D_oEopD_1P$) were compared with the same bleaching sequences containing D_{HT} stage, it was observed that not only the consumption of ClO_2 reduced but the brightness and brightness stability improved, the HexA content in final bleached pulps reduced and the AOX generation in the effluents reduced (Table 3).

ECF bleaching in modified sequences

ECF bleaching of 40% hardwood and 60% bamboo pulp was also done by using $D_0E_{OP}PD_1$ and $D_0E_{OP}D_1ED_2$ sequences with and without D_{HT} stage at kappa factor of 0.33. The brightness development in case of $D_0E_{OP}D_1ED_2$, $D_0E_{OP}PD_1$ sequences were better as compared to $D_0E_{OP}D_1D_2$ sequence. Brightness was 89.1, 90.1 and 90.5 % ISO and CIE whiteness was 82.6, 83.8 and 85.7 in $D_0E_{OP}D_1D_2$, $D_0E_{OP}PD_1$ and

$D_0E_{OP}D_1ED_2$ sequences respectively (Table 4). It was observed that $D_0E_{OP}D_1ED_2$, $D_0E_{OP}PD_1$ sequences consumed ~9 % less ClO_2 than $D_0E_{OP}D_1D_2$. However, in these sequences peroxide and sodium hydroxide consumption was more (Table 4). Use of D_{HT} stage reduced the dioxide requirement and improved the brightness and brightness stability in comparison with the reference sequences (without D_{HT} treatment). The dioxide requirement reduced by ~ 15% in case of $D_{HT}E_{OP}D_1ED_2$, $D_{HT}E_{OP}PD_1$ sequences. Brightness achieved was 89.5, 90.3 and 90.6 % ISO and CIE whiteness was 83.7, 84.7 and 86.2 in $D_{HT}E_{OP}D_1D_2$, $D_{HT}E_{OP}PD_1$ & $D_{HT}E_{OP}D_1ED_2$ sequences respectively (Table 4). Thus, 40% hardwood and 60% bamboo pulp can be bleached to high brightness level using $D_{HT}E_{OP}D_1ED_2$, $D_{HT}E_{OP}PD_1$ sequences without oxygen delignification.

B. 80% hardwood and 20% bamboo pulp

Kappa factor optimization

ECF bleaching of 80% hardwood and 20% bamboo pulp was conducted in $D_0E_{OP}D_1D_2$ sequence at 0.20, 0.22, 0.25, 0.30, 0.33 and 0.35 Kappa factor. It was found that a brightness of 90^+ % ISO could be achieved at a kappa factor of 0.22 (Table 5).

ECF bleaching of 80% hardwood and 20% bamboo pulp with and without hot chlorine dioxide

A number of experiments were conducted in $D_0E_{OP}D_1D_2$ sequence at 0.20, 0.22 and 0.25 Kappa factor with and without hot chlorine dioxide (D_{HT}) stage in each case. Experiments were also performed at 20, 25, 30 and 35 % reduction in ClO_2 dose in D_{HT} stage at each Kappa factor to find out the maximum possible saving in chlorine dioxide with the use of hot D stage without compromising on the other parameters. It was found that up to 30% ClO_2 can be saved in the first bleaching stage when hot chlorine dioxide was used in the initial D stage at all the Kappa factors (data not shown). Also better brightness, whiteness and brightness stability were obtained as compared to the reference sequences. Brightness was 89.9, 90.4, 90.6, 91.0, 91.0 and 91.5 % ISO and CIE whiteness was 82.6, 83.6, 85.4, 86.4 86.9 and 87.9 in case of $D_0E_{OP}D_1D_2$, $D_{HT}E_{OP}D_1D_2$ (0.20 kappa factor), $D_0E_{OP}D_1D_2$, $D_{HT}E_{OP}D_1D_2$ (0.22 kappa factor) and $D_0E_{OP}D_1D_2$, $D_{HT}E_{OP}D_1D_2$ (0.25 kappa factor) sequences respectively (Table 6). With the use of D_{HT} stage, total chlorine dioxide consumption reduced by 15.7%, 16.5% and 17.3% at a kappa factor of 0.20, 0.22 and 0.25 respectively (Table 6) and AOX generation also reduced.

ECF bleaching using modified sequences

ECF bleaching of 80% hardwood and 20% bamboo pulp was also carried out by using $D_0E_{OP}PD_1$ & $D_0E_{OP}D_1D_2$ sequences with and without D_{HT} stage at a kappa factor of 0.22. The brightness development in case of $D_0E_{OP}PD_1$ sequence was better as compared to $D_0E_{OP}D_1D_2$ sequence. Brightness was 90.6 and 91.4 % ISO and CIE whiteness was 85.4 and 86.4 in $D_0E_{OP}D_1D_2$,

Table 4: ECF bleaching of 60% hardwood and 40% bamboo pulp in modified sequences Comparison of bleached pulp properties and bleach chemical requirement

Bleaching sequence	Kappa factor	Brightness (%ISO)	CIE whiteness	Viscosity (cp)	Bleached yield (%)	PC no.	NaOH (kg/TP)	H_2O_2 (kg/TP)	ClO_2 (kg/TP)	AOX (kg/TP)
$D_0E_{OP}D_1D_2$	0.33	89.1	82.6	14.1	93.4	0.42	18.0	**5.0**	**35.8**	**1.04**
$D_0E_{OP}PD_1$	0.33	90.1	83.8	14.3	93.6	0.39	24.5	**10.0**	**32.5**	**0.74**
$D_0E_{OP}D_1ED_2$	0.33	90.5	85.7	14.1	93.8	0.40	21.5	**7.0**	**32.5**	**1.00**
$D_{HT}E_{OP}D_1D_2$	0.33	89.5	83.7	13.9	93.5	0.38	18.0	**5.0**	**30.8**	**0.80**
$D_{HT}E_{OP}PD_1$	0.33	90.3	84.7	14.0	93.7	0.33	24.5	**10.0**	**27.8**	**0.65**
$D_{HT}E_{OP}D_1ED_2$	0.33	90.6	86.2	13.7	93.6	0.30	21.5	**7.0**	**27.8**	**0.79**

Table 5: ECF Bleaching of 80% hardwood and 20% bamboo pulp in $D_0E_{OP}D_1D_2$ sequence at different kappa factors Comparison of bleached pulp properties and bleach chemical consumption

Kappa factor	Brightness (%ISO)	CIE whiteness	Viscosity (cp)	PC no.	Bleached yield (%)	NaOH (kg/TP)	H_2O_2 (kg/TP)	ClO_2 (kg/TP)
0.20	**89.9**	82.6	18.2	0.34	96.0	16.0	5.0	23.0
0.22	**90.6**	85.4	17.9	0.31	95.3	16.0	5.0	24.2
0.25	**91.0**	86.9	17.5	0.29	95.6	16.0	5.0	26.0
0.30	**91.6**	88.3	16.8	0.28	95.5	16.0	5.0	29.0
0.33	**91.8**	89.0	16.5	0.26	95.3	16.0	5.0	30.8
0.35	**91.9**	88.9	15.9	0.24	95.4	16.0	5.0	32.0

Table 6: Effect of hot chlorine dioxide in ECF bleaching of 80% hardwood and 20% bamboo pulp Comparison of bleached pulp properties, bleach chemical requirements and AOX generation

Bleaching sequence	Kappa factor	Brightness (%ISO)	CIE whiteness	Bleached yield (%)	Viscosity (cp)	PC no.	HexA in bld. pulp (mmol/kg)	NaOH (kg/TP)	H_2O_2 (kg/TP)	ClO_2 (kg/TP)	AOX (kg/TP)
$D_0E_{OP}D_1D_2$	0.20	**89.9**	**82.6**	**96.0**	**18.2**	**0.34**	**2.00**	**15.0**	**5.0**	**23.0**	**0.57**
$D_{HT}E_{OP}D_1D_2$	0.20	**90.4**	**83.6**	**95.6**	**17.6**	**0.30**	1.42	15.0	**5.0**	**19.4 (- 3.6)**	**0.45**
$D_0E_{OP}D_1D_2$	0.22	**90.6**	**85.4**	**95.3**	**17.9**	**0.31**	1.95	15.0	**5.0**	**24.2**	**0.62**
$D_{HT}E_{OP}D_1D_2$	0.22	**91.0**	**86.4**	**95.4**	**17.3**	**0.28**	1.38	15.0	**5.0**	**20.2 (- 4.0)**	**0.52**
$D_0E_{OP}D_1D_2$	0.25	**91.0**	**86.9**	**95.6**	**17.5**	**0.29**	1.90	15.0	**5.0**	**26.0**	**0.73**
$D_{HT}E_{OP}D_1D_2$	0.25	**91.5**	**87.9**	**95.1**	**16.8**	**0.24**	1.29	15.0	**5.0**	**21.5 (- 4.5)**	**0.60**

Table 7: ECF bleaching of 80% hardwood and 20% bamboo pulp in modified sequences Comparison of bleached pulp properties; bleach chemical requirement and AOX generation

Bleaching sequence	**Kappa factor**	**Brightness (%ISO)**	**CIE whiteness**	**Viscosity (cp)**	**Bleached yield (%)**	**PC no.**	**NaOH (kg/TP)**	**H_2O_2 (kg/TP)**	**ClO_2 (kg/TP)**	**AOX (kg/TP)**
$D_0E_{OP}D_1D_2$	0.22	90.6	85.4	17.9	95.3	0.31	15.0	**5.0**	**24.2**	**0.62**
$D_0E_{OP}PD_1$	0.22	91.4	86.4	18.2	96.0	0.28	21.8	**10.0**	**21.2**	**0.55**
$D_{HT}E_{OP}D_1D_2$	0.22	91.0	86.4	17.3	95.4	0.28	15.0	**5.0**	**20.2**	**0.52**
$D_{HT}E_{OP}D_1ED_2$	0.22	91.9	87.9	17.0	95.5	0.23	22.6	**7.0**	**19.2**	**0.51**
$D_{HT}E_{OP}PD_1$	0.22	91.5	87.0	17.6	95.4	0.25	21.8	**10.0**	**17.2**	**0.45**

$D_0E_{OP}PD_1$ sequences respectively (Table 7). With the use of D_{HT} stage, chlorine dioxide consumption reduced and also brightness and brightness stability improved in comparison to the reference sequences. $D_{HT}E_{OP}D_1D_2$ and $D_{HT}E_{OP}PD_1$ sequences consumed 16.5 % and 18.9 % less ClO_2 in comparison to the reference sequences ($D_0E_{OP}D_1D_2$, $D_0E_{OP}PD$) (Table 7). Brightness was 91.0 and 91.5 % ISO and CIE whiteness was 86.4 and 87.0 in case of $D_{HT}E_{OP}D_1D_2$ and $D_{HT}E_{OP}PD_1$ sequences respectively (Table 7). Significant improvement in pulp whiteness (87.9) was observed when $D_{HT}E_{OP}D_1$ pulp was subjected to second extraction stage and then subjected to D_2 stage.

CONCLUSIONS

Bleachability of 80% hardwood and 20% bamboo pulp is better as compared to 40% hardwood and 60% bamboo pulp in ECF sequence and it requires the lowest kappa factor of 0.22 to bleach to 90+ brightness levels (0.33 in case of 40% hardwood and 60% bamboo pulp). The substitution of standard D_0 stage with hot D stage (D_{HT}) in conventional ECF bleaching causes reduction in HexA content, which helps in improving the brightness and other optical properties. It also helps in reducing the chlorine dioxide consumption and hence the generation of AOX.

It is possible to achieve AOX level < 1.0 kg/TP in case of 40% hardwood and 60% bamboo pulp and 0.5 kg/TP in case of 80% hardwood and 20% bamboo pulp when bleached in $D_{HT}E_{OP}D_1D_2$, $D_{HT}E_{OP}D_1ED_2$, $D_{HT}E_{OP}D_1P$ and $D_{HT}E_{OP}PD_1$ sequences without oxygen delignification. Pulp properties also improve when first or second D stage is replaced with P stage ($D_OE_{OP}D_1P$, $D_OE_{OP}PD_1$, $D_{HT}E_{OP}D_1P$ and $D_{HT}E_{OP}PD_1$) or when the second extraction stage ($D_OE_{OP}D_1ED_2$ and $D_{HT}E_{OP}D_1ED_2$) is used.

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