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Influence of Kappa Number on Enhancing Pulp Brightness through Stage D0 with ClO2 Bleaching Process: Environmental Implications and Considerations

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Abstract

Stage D0 in the pulp bleaching process, utilizing Chlorine Dioxide (ClO2), represents a critical phase aimed at improving pulp brightness while simultaneously addressing environmental concerns. This stage enhancement of pulp brightness can made an environmental impact, as excessive usage can lead to harmful emissions and environmental degradation. The amount of ClO_2 used at stage D0 is influenced by the kappa number, the greater the kappa number, the greater the ClO_2 use will be to produce brightness that corresponds to standar. The calculation of ClO_2 usage at stage D0 is carried out after obtaining data related to ClO_2 and the amount of pulp production from DCS (Distribute Control System). Based on the results of calculations and analysis, it can be concluded that the kappa number influences the total use of ClO_2 in stage D0. The more ClO_2 used in the D0 tower will produce pulp with a higher level of brightness.

Keywords: Bleaching, ClO_2, Kappa number, D0 tower.

INTRODUCTION

The pulp industry, vital for the production of paper and packaging materials, stands at the intersection of economic necessity and environmental responsibility. One of the key processes within pulp manufacturing, the bleaching stage, is central to achieving desired paper quality, particularly in terms of brightness and appearance. However, the use of Chlorine Dioxide (ClO_2) in the bleaching process raises significant environmental concerns due to its potential adverse impacts on air and water quality. Understanding and addressing these environmental implications are crucial for promoting sustainable practices within the pulp industry.

Chlorine Dioxide (ClO_2) is widely utilized as a bleaching agent in pulp processing due to its effectiveness in removing lignin and enhancing pulp brightness. However, the use of ClO_2 can lead to the formation of harmful by-products, including chlorinated organic compounds and chlorate ions, which pose risks to human health and the environment. Additionally, ClO_2 bleaching processes may contribute to water pollution through the discharge of wastewater containing residual ClO_2 and its by-products, impacting aquatic ecosystems and biodiversity.

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Furthermore, the environmental impact of ClO_2 bleaching extends beyond water pollution to air quality concerns. The release of chlorine-based compounds during ClO_2 bleaching operations can result in the emission of hazardous air pollutants, such as chlorine gas and dioxins, which have been linked to respiratory issues and environmental contamination. As such, mitigating the environmental footprint of ClO_2 bleaching processes is imperative for promoting environmental sustainability within the pulp industry.

The bleaching stage is the most important stage in the pulp making processand can determine the quality of the pulp. This stage aims to remove the color of the pulp to increase the brightness level pulp) The color of the dominant pulp is darkbrownish. Lignin contained in largeamounts causes discoloration of the pulp. Therefore, the effectiveness of lignin removal at the bleaching stage is a factor that really determines the brightness results. Bleaching promotes an increase in the brightness of the pulp and is followed by washing and pressing [1]. The measurement of lignin content in pulpis called the kappa number. If the kappa number is high, the color of the resulting pulp tends to be dark and vice versa. Therefore, to remove lignin levels, bleaching is carried out.

Kappa number measurement also plays a role in controlling efficiency and environmental impacts in the pulp industry. By measuring and controlling the Kappa number accurately, pulp mills can optimize the consumption of delignification chemicals such as bleaches and other chemical reagents. This not only reduces production costs, but also helps reduce environmental impact due to more efficientuse of chemicals. In addition, environmental regulations often limit theamount of chemical waste that can be discharged into the environment, someasuring the Kappa number helps the pulpindustry comply with these standards by optimizing the delignification process and reducing the chemical waste produced. Thus, measuring the Kappa number is not only important in producing quality pulp, but also in maintaining a balance between process efficiency and environmentalimpact in the pulp industry.

The lignin removal process is carried out using ClO_2. ClO_2 levels andconcentrations are variables that play the most important role in the pulp whitening process. Adding ClO_2 that is too low will cause the color of the resulting pulp to tendto be dark. However, if too much ClO_2 is added, even though the color of the pulp will be brighter, it will cause damage to the pulp. Apart from stage D0, the bleaching stage will be continued at the EO stage which uses H_2O_2 as a bleaching liquid andcontinues to stages D1 and D2 which againuse ClO_2 as a bleaching liquid to whiten thepulp and dissolve lignin.

Chemical Components of Wood

Cellulose is the main part of woodcell walls in the form of a glucose carbohydrate polymer and has the samecomposition as starch. In 1838, the identification of cellulose as a fundamental component of plant cells was attributed to the findings of the French botanist Anselme Payen. Payen, for the first time, extracted cellulose from wood, leading to the acknowledgment of its significance in plant cellular structure [2]. Some glucose and cellulose molecules have the same composition as starch. Several cellulose molecules form a cellulose chain. Celluloseis also a polysaccharide that forms a cellulose chain. Cellulose is also a polysaccharide which indicates that it contains sugar compounds. The chemical formula identifies that it contains sugar compounds. The chemical formula forcellulose is ($C_6H_{10}O_5$) where "n" is the number of repetitions of glucose units where "n" is the number of repetitions of glucose units. The other main wood constituents, hemicelluloses and lignin, have been dissolved in the cooking and bleaching stages and consequently the pulp yield is low [3].

Hemicellulose is also formed fromsugar as its main component. Unlikecellulose, it is only a polymer of 5 differenttypes of polymers, namely Glucose, Mannose, Galactose, Xylose and Arabinose. Hemicellulose has a degree of polymerization of 300 and below. During pulping, hemicellulose reacts faster than cellulose. Cellulose is quite resistant in the process of reacting more quickly than cellulose.

Lignin is a complex polymer found in plant cell walls, an important component in the pulp and paper industry. In general, the process of making paperpulp involves separating lignin from cellulose and hemicellulose fibers using various chemical and physical methods. This process is known as pulp bleaching, which aims to produce cleaner pulp and purer cellulose fiber. Although lignin has apositive contribution to the strength andstability of wood, its presence in finished paper can cause weakness and yellowing inpaper products. Therefore, reducing the amount of lignin in pulp has become a major focus in pulp industry research.

Kappa Number

The Kappa number is a parameterused to determine the lignin content in the pulp and is used to determine the level of maturity or whitening power of the pulp (SNI 0494-1989A). Kappa number is a measure of the lignin content of the pulp, ahigher kappa number indicates a higher lignin content. As the Kappa number and lignin content decreased, depolymerisation and dissolution of the hemicelluloses and cellulose began to occur [4]. Something similar is the permanganate number (or K number). The Kappa number is used to monitor the amount of chemical pulp delignification after pulping and between bleaching stages.Monitoring the Kappa number of bleached pulp and then could be helpful to reducing the extra chemical and energy consumptions in the pulp and paper industry. The amount of bleaching agent needed willbe closely related to the lignin content of the pulp, so the kappa number plays an important role in controlling the delignification process as well as several parameters in the bleaching process. The lignin content in unbleached pulp is neededbecause in the initial stage of the bleaching process it is necessary to remove the remaining lignin content after the cooking process. In the pulp and paper industry the expected kappa value is as low as possible.A low pulp kappa number indicates that theresidual lignin content is relatively low, thematurity level of the pulp is high and the degree of delignification is high. The high remaining lignin will provide stiffness to the fiber weave and the sheets formed are rough, resulting in low strength.

Viscosity

Viscosity is a measurement thatstates the viscosity of a fluid or liquid. The viscosity parameter is closely related to flow resistance, so viscosity is needed to determine how fast a liquid will flow. Viscosity in a fluid causes friction betweenthe moving parts of the fluid layer. Viscosity of pulp gives an estimate of the average degree of polymerization of cellulose in the pulp. It indicates cellulose integrity and the relative molecular weight during pulping/bleaching process [5]. The viscosity standard for digester output pulp at Pulp and Paper Industry is 23 mpas. The viscosity of the liquid will cause friction between the moving parts of the liquid layer.

Determination of lignin content and fiber strength is important for wood analysis and pulp characterization. The amount of remaining lignin is usually expressed by the kappa number and thefiber strength is expressed as viscosity. To achieve both, you must pay attention to theconcentration of NaOH used. If the use of NaOH is low, the lignin removal process will be less good, resulting in rejects or chips where only part of them will cook andthe kappa number and viscosity obtained will be higher. On the other hand, when using high concentrations of NaOH, thecellulose fibers will also be attacked and damaged, resulting in low viscosityproduced, as a result, the wood chips are toocooked and the kappa number obtained willbe lower.

Bleaching

Bleaching is a chemical process carried out to remove residual lignin from the pulping process. Bleaching process of chemical pulp is multistage sequential procedure carried out with two or more chemicals to achieve high pulp brightness [6]. Eucalyptus sp. pulp bleaching usually employs bleaching sequences consisting of four or more alternating bleaching stages to eliminate the residual lignin and chromophores [7]. To remove residual lignin, an oxidation process is carried out followed by a bleaching reaction. The fiberbleaching process must use reactivechemicals to dissolve the lignin content in the fiber to obtain a high degree ofbrightness. However, the use of chemicals must always be controlled so as not to causedangerous environmental pollution. Pulp and Paper Industry that using the Elemental Chlorine Free (ECF) processes,which is a bleaching process using chlorinecompounds in the form of

ClO_2 and also adding peroxide to increase the degree of whiteness if the degree of whiteness is not achieved. Few of the large sized wood or agro based pulp mills have started elemental chlorine free bleaching process with use of chlorine dioxide (ClO_2) [8].

ClO_2

Chlorine dioxide is one of the most efficient bleaching agents for the elemental chlorine free (ECF) bleaching process. The bleaching mechanism of chlorine dioxide is extremely complex and involves a series of chemical reactions. The reaction of residual lignin in pulp with chlorine dioxide induces structural changes in the residual lignin, which is the main cause of chlorine dioxide bleaching [9]. In comparison to the total chlorine free (TCF) bleaching method, ECF has advantages of high brightness after bleaching, low chemical consumption, and low-cost operation. Chlorine dioxide is an efficient and environmentally friendly oxidant and disinfectant [10].

ClO_2, or chlorine dioxide, is a chemical compound consisting of onechlorine atom and two oxygen atoms. Chlorine dioxide was discovered in 1811 by Sir Humphry Davy and since the mid-20th century, it has been widely used in the paper industry as a bleach and for the treatment of drinking water [11]. One of the main uses ofClO_2 is as a bleaching and disinfectant agent. Due to its strong oxidative properties, ClO_2 is often used to clean drinking water, remove harmfulmicroorganisms, and remove unpleasant odors. Apart from that, ClO_2 is also used inthe food processing industry, pulp and paper industry, and in waste water treatment. However, the use of ClO_2 must be done with caution because it is reactive and potentially dangerous if not handled properly.

Chlorine dioxide (ClO_2) is a specific oxidizing agent for lignin removal and provides good quality pulp of high brightness, without carbohydrates degradation [12]. This reduces negative impacts on the environment and follows sustainable trendsin the pulp and paper industry. In addition, ClO_2 can also be used in combination with other whitening methods, such as chlorine,to achieve optimal whitening results. However, it is important to remember that the use of ClO_2 must be done carefully, following strict safety guidelines and environmental regulations, to ensure that its use is safe for workers and the environmentaround the pulp mill.

RESEARCH METHODOLOGY

This research using materials such as cellulose as chemical compound of wood, bleaching such as Chlorine Dioxide or ClO_2, D0 stage and kappa number on pulp samples.

Time and Place of Research

The research was carried out on 15 July-15August 2023. The research was carried outin the aeration pond section of the Effluent Treatment Plant at the Pulp & Paper Industry, which located in Muara Enim, South Sumatra.

Data Collection

To achieve the aim of the special task, namely analyzing the amount of ClO_2 used for optimal pulp quality based on the parameters kappa number, viscosity and brightness at the D0 stage bleaching plant at Pulp & Paper Industry, there are several things that need to be done as in Figure 1.

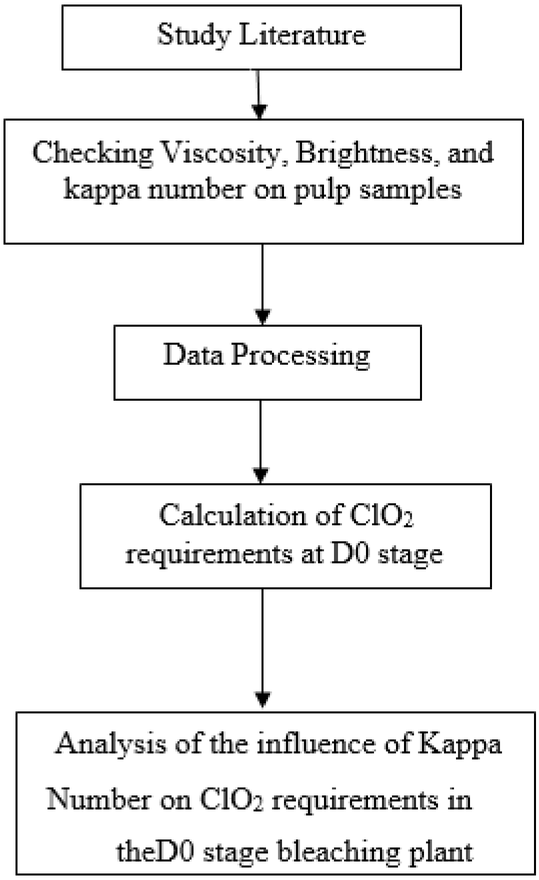

Figure 1. Flow diagram for carrying out special tasks

Calculation

The required data was obtained from the results of Pulp and Paper Industry's main laboratory analysis Pulp & Paper which is then sent to the Distribute Control System (DCS). Based on observations made at DCSand in the field on the D0 Tower tool, data was collected in August - September 2023 as shown in Figure 1.

Table 1. Calculating total production basedon total pulp flow and pulp consistency

Flow ClO_2	konsentrasi	ClO_2 *Charge*	
m3/h	g/l	Kg/h	kg/adt
82.27	9.00	740.42	10.95
86.45	8.90	769.40	12.02
73.11	8.90	650.72	12.39
83.77	9.00	753.89	12.10
89.47	9.00	805.22	12.40
91.11	8.90	810.89	12.99
91.82	9.00	826.36	13.47
91.58	9.00	824.25	13.25
94.24	9.10	857.58	13.87
94.12	9.20	865.89	13.59
97.08	9.00	873.72	13.52
97.39	9.10	886.21	13.20
96.15	9.20	884.59	13.65
96.55	9.10	878.62	14.83

Table 2. Calculation results of ClO_2 use at D0 Stage Bleaching Plant

Flow inlet press 2nd post			*Consistensi inlet 2nd press*	Pulp *production*	
1	2	Total			
m3/h	m3/h	m3/h	%	BD T/h	ADT/h
493.0	491.2	984.2	6.0	60.8	67.5
445.0	476.4	921.4	5.9	57.6	64.0
477.8	486.5	964.3	6.0	47.2	52.5
465.8	470.7	936.5	5.9	56.0	62.2
426.1	474.4	900.5	6.0	58.4	64.9
427.5	472.4	899.9	5.9	56.1	62.4
475.8	475.2	951.0	6.0	55.2	61.3
440.8	464.2	905.0	5.9	55.9	62.2
471.0	475.4	946.4	5.9	55.6	61.8
479.2	476.4	955.6	6.0	57.3	63.7
493.1	492.3	985.4	5.9	58.1	64.6
496.3	491.6	987.9	6.1	60.4	67.1
488.5	488.07	976.6	5.9	58.3	64.8
452.8	447.7	900.5	5.9	53.3	59.2

Calculation of Total Production (Adt/h)

- Calculation of Total Production (Adt/h)

$$= \frac{Total\ Flow\left(\frac{m^3}{h}\right) x \frac{Consistensi\ inlet\ 2nd\ press}{100}}{0.9} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

- Calculation of ClO_2 *charge* (Kg/h)

$$= Flow\ ClO2\ (m^3h)\ x\ Konsentrasi\ ClO2(g/l) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

- Calculation of ClO_2 *Charge* (Kg/Adt)

$$= \frac{ClO2\ charge\ (Kg/h)}{Production\ (ADT/h)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

RESULTS AND DISCUSSION

Comparison of kappa number and ClO_2 charge per hour

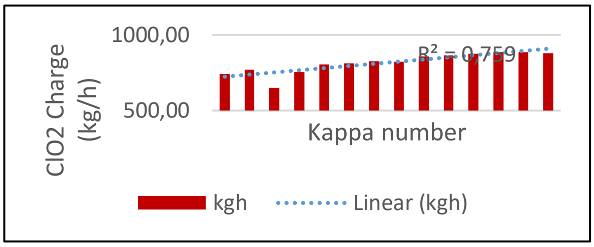

Figure 1. Relationship between kappa numberand ClO2 charge per hour

The graph above shows that the higher the kappa number value, the greater the amount of ClO2 needed to bind lignin in the pulp and vice versa, if the kappa number value is low, then not too much ClO2 is needed. However, in some cases there was a decrease in the use of ClO_2, this was due to differences in the amount of pulp production at that time. A decrease in the amount of pulp production and flow rate will also affect the use of ClO_2 which will also decrease.

Based on theory, the higher the kappa number value, the higher the lignin content in the pulp. The higher the lignin content means the higher the ClO_2 needed to degrade the lignin content in the pulp sothat the brightness of the pulp will increase.However, it can be seen in the graph abovethat the kappa number 9.45 value uses $ClO_2$of 650.72 Kg/h and is smaller whencompared to pulp with kappa number 9.44 which uses ClO_2 of 769.40 Kg/h. The decrease in ClO_2 use is due to the fact that determining the use of ClO_2 has several factors that must be considered besides thekappa number. One factor that greatly influences the use of ClO_2 is the amount ofpulp produced in the process, where the more pulp produced, the more ClO_2 that must be used in the bleaching process.

Relationship between Kappa number and Usage per Adt

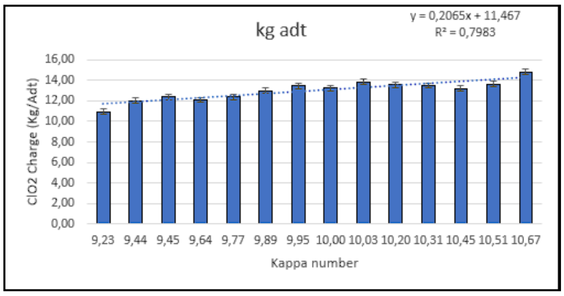

Figure 2. Relationship between kappa number and ClO_2 charge per ADT

The graph above shows that the kappa number value is linear with the ClO_2 requirement. In the graph it can be seen that pulp with a low kappa number requires lessClO_2 than pulp with a higher kappa number. Pulp with kappa number 9.23 requires 10.95 Kg/ADT of ClO_2. The need for ClO_2 is much less than the need for ClO_2 forkappa number 10.67 which requires 14.83 Kg/ADT of ClO_2. The reason for using a higher ClO_2 requirement for pulp with a largerkappa number is because it is in accordancewith the function of ClO_2, namely to reducethe amount of lignin content in the pulp.

Relationship between Kappa number and Brightness

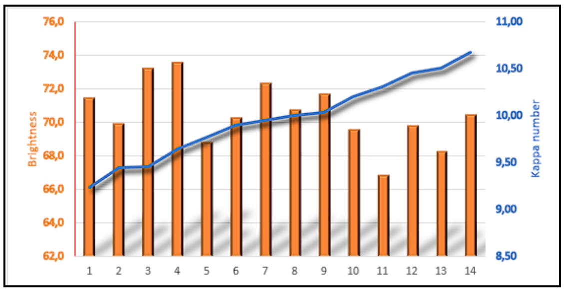

Figure 3. Relationship between Kappa number and Brightness

The relationship between kappa number and brightness is that an increase inkappa number will usually cause a decreasein brightness, because more lignin remainsin the pulp. Conversely, if the kappa number value is reduced through an effective bleaching process, the brightness will increase because the dark color caused by lignin has been removed. The delignifcation to a lower kappa number is one of the factors to get high pulp brightness [12].

The theory regarding the relationship between kappa number and brightness of the pulp above is in accordance with the graph shown. In the graph it can be seen that the highest brightness value produced at stage D0 is 73.21 % ISO because the pulp sample data has a low kappa number value at D0 towerinlet, namely 9.45. The lowest brightness ofthe pulp is 66.85 % ISO because the pulp sample in this data has a kappa number value which is quite high at the D0 tower stage, namely 10.31.

The values of brightness and kappanumber in the D0 tower influence the amount of ClO_2 used charge. The large needfor the use of ClO_2 will improve the qualityof the pulp in terms of brightness. Pulp brightness increased and viscosity decreased with increasing ClO_2 charge in bleaching stage [13]. Pulp sample data number 1 shows that pulp withan inlet Kappa number D0 9.23 only requires a ClO_2 charge of 10.95 kg/adt toproduce pulp with a brightness of 71.4% ISO. The amount of ClO_2 required is much less compared to the kappa 10.63 sample which requires 14.83 kg/adt of ClO_2 to produce pulp with a brightness of 70.4 % ISO.

Relationship between Kappa number and pulp viscosity

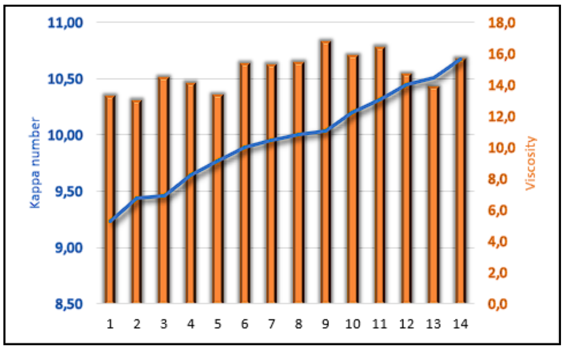

Figure 4. Relationship between Kappa numberand Pulp Viscosity

One of the side effects of the bleaching process that needs to beconsidered is the degradation of cellulose, because this will cause a decrease in fiber strength which results in a decrease in the tensile strength of the paper as the final result [14]. The lignin content in the pulp is what binds the fibers in the pulp such as cellulose andhemicellulose, as a result the strength of thepulp fibers will decrease. On the other hand,a lower viscosity often indicates that the fibers in the pulp separate and move aroundeach other more easily. This can increase the potential of the fibers to withstand pressure, tension and bending in the resulting pulp.

It can be seen in the graph that the pulp has a low kappa number, namely 9.23. The viscosity of this pulp is also relatively low, namely 13.3 mPa.s. The low viscosity of this pulp indicates that the fibers in the pulp such as cellulose and hemicellulose are more easily separated or are not bound to large amounts of lignin because the kappa number is low. The highest viscosityis 16.8 mPa.s. The reason for the high viscosity is because the kappa number in the pulp is 10.03. A high kappa number means that there is still a lot of lignin content that binds the fibers in the pulp. The minimum standard for the viscosity of the D0 bleaching stage is 11.0 mPa.s which in the next bleaching stage is expected to continue to decrease in line with the processso that at the end it is able to produce pulp with the expected physical properties.

CONCLUSION AND SUGGESTION

Conclusion

In conclusion, the utilization of Chlorine Dioxide (ClO_2) in the bleaching process at the D0 stage is intricately tied to the lignin content present in the pulp. As observed, higher lignin content necessitates a corresponding increase in ClO_2 usage to achieve desired brightness levels. This underscores the importance of considering pulp composition when determining ClO_2 application rates to minimize environmental impact.

Several factors influence the quantity of ClO_2 utilized in the D0 stage bleaching plant, including the kappa number, production volume, and ClO_2 flow rate. A higher kappa number signifies greater lignin content, resulting in heightened ClO_2 requirements. Moreover, increased production volume directly correlates with higher ClO_2 flow rates, necessitating careful monitoring and control to optimize ClO_2 utilization while ensuring optimal bleaching outcomes.

It is essential to maintain a delicate balance between ClO_2 usage and bleaching production to achieve optimal brightness levels while minimizing environmental repercussions. Calculating ClO_2 flow rates requires meticulous attention to ClO_2 consumption and bleaching production, ensuring the pulp reacts optimally to attain prescribed brightness standards. Additionally, it is noteworthy that higher kappa number values correspond to elevated viscosity but lower pulp brightness, further emphasizing the intricate relationship between process parameters and pulp quality.

In light of these findings, it is imperative for the pulp industry to adopt sustainable practices that prioritize environmental conservation without compromising product quality. By leveraging insights from this study, stakeholders can develop strategies to mitigate environmental impact while maintaining operational efficiency in ClO_2 bleaching processes, thereby advancing towards a more sustainable future for the pulp industry.

Suggestion

Bleaching process, especially at stage D0, has an important role in processing chips into pulp and removing lignin content and improving pulp quality. Therefore, the author suggests that before using ClO_2, you should calculate the use of ClO_2 theoretically and control it in the DCS Room, so that the desired brightness value is achieved and do not use ClO_2 excessively.Checking samples must go through an accurate process and in accordance with procedures so that there are no errors in datacollection which can cause errors in taking action. Analysis of the amount of ClO_2 usedis very necessary, because if not enough ClO_2 is used in the bleaching process, the brightness target will not be achieved, thereby reducing the quality of the pulp. Excessive use of ClO_2 will affect the amount of residue that is wasted too much and can also have an impact on fiber damage in the pulp.

REFERENCES

A. M. Sousa, I. S. S. Pinto, L. Machado, L. Gando-Ferreira, and M. J. Quina, "Sustainability of kraft pulp mills: Bleaching technologies and sequences with reduced water use," J. Ind. Eng. Chem., vol. 125, pp. 58–70, 2023, doi: 10.1016/j.jiec.2023.05.033.

M. Butnariu and A. Ionut-flavius, "Journal of Biotechnology and Bioprocessing General Information about Cellulose," no. January, 2022, doi: 10.31579/2766-2314/077.

E. Brännvall and C. Aulin, "CNFs from softwood pulp fibers containing hemicellulose and lignin," Cellulose, vol. 29, no. 9, pp. 4961–4976, 2022, doi: 10.1007/s10570-022-04585-8.

E. Małachowska, M. Dubowik, A. Lipkiewicz, K. Przybysz, and P. Przybysz, "Analysis of cellulose pulp characteristics and processing parameters for efficient paper production," Sustain., vol. 12, no. 17, pp. 1–12, 2020, doi: 10.3390/su12177219.

"BioRes_16_4_8111_Hsieh_LKYL_Effects_Residual_Phenolics_Xylanse_ClO2_Bleach_HW_Kraft_19068." Taipei, Republic of China.

N. Sharma, N. K. Bhardwaj, and R. B. P. Singh, "Environmental issues of pulp bleaching and prospects of peracetic acid pulp bleaching: A review," J. Clean. Prod., vol. 256, 2020, doi: 10.1016/j.jclepro.2020.120338.

E. Isaza Ferro, K. Ruuttunen, J. Perrin, and T. Vuorinen, "Sustainable bleaching of Eucalyptus sp. kraft pulp with hypochlorous acid, ozone and hydrogen peroxide," Ind. Crops Prod., vol. 172, no. June, 2021, doi: 10.1016/j.indcrop.2021.114004.

G. Singh, S. Kaur, M. Khatri, and S. K. Arya, "Biobleaching for pulp and paper industry in India: Emerging enzyme technology," Biocatal. Agric. Biotechnol., vol. 17, pp. 558–565, 2019, doi: 10.1016/j.bcab.2019.01.019.

M. Lei et al., "Kinetics of the reaction between a lignin model compound and chlorine dioxide," Chem. Eng. J., vol. 393, no. November 2019, p. 124783, 2020, doi: 10.1016/j.cej.2020.124783.

J. He et al., "New System for Efficient Removal of Lignin with a High Proportion of Chlorine Dioxide," Sustain., vol. 15, no. 4, 2023, doi: 10.3390/su15043586.

C. M. C. Andrés, J. M. P. de la Lastra, C. Andrés Juan, F. J. Plou, and E. Pérez-Lebeña, "Chlorine Dioxide: Friend or Foe for Cell Biomolecules? A Chemical Approach," Int. J. Mol. Sci., vol. 23, no. 24, 2022, doi: 10.3390/ijms232415660.

T. Ferdous, M. A. Quaiyyum, and M. S. Jahan, "Chlorine dioxide bleaching of nineteen non-wood plant pulps," Nord. Pulp Pap. Res. J., vol. 35, no. 4, pp. 569–576, 2020, doi: 10.1515/npprj-2020-0043.

M. Haque, M. Nanjiba, M. Sarwar Jahan, M. A. Quaiyyum, M. Z. Alam, and J. Nayeem, "Pre-bleaching of kraft acacia pulp," Nord. Pulp Pap. Res. J., vol. 34, no. 2, pp. 165–172, 2019, doi: 10.1515/npprj-2018-0082.

A. M. Fuadi and S. H, "Pemutihan Pulp dengan Hidrogen Peroksida," Reaktor, vol. 12, no. 2, pp. 123–128, 2008.