IMPACT OF COOKING CONDITIONS ON PULP YIELD AND OTHER PARAMETERS

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ABSTRACT

Two laboratory studies using multiple white liquor additions and multiple black liquor extractions were carried out to investigate the impact of cooking conditions on pulp yield and other parameters. Results from the first study (alkali profiles at a constant cooking temperature) indicate that cellulose yield shows a good correlation with pulp yield and is significantly affected by alkali profiles. A higher alkali charge to the impregnation stage shows the most negative impact on cellulose yield. There is no significant difference in xylan yield between different alkali profiles. In addition, it was found that xylan content does not correlate with the pulp yield. In spite of obtaining higher cellulose yield when adding more alkali in the wash zone, a lower pulp yield is obtained at a given kappa number due to lower delignification rate. The results from the second study indicates that cooking temperature does not affect the pulp yield and HexA content at a given kappa number but lower pulp viscosity is obtained from a higher temperature cook. The positive effect of higher H-factor at a higher cooking temperature on pulp yield, pulp viscosity, and HexA content is also reported.

INTRODUCTION

Lo-Solids® Cooking is a unique pulping method maintaining both an even alkali concentration and lower dissolved wood solids throughout the cook. The laboratory study clearly demonstrates that by decreasing the concentration of dissolved wood solids in the black liquor, pulp strength and bleachability are improved and also white liquor consumption decreases (1, 2). Since the introduction of Lo-Solids cooking in 1993, there are over 60 digesters around world using this innovative cooking process. These mills reported many benefits such as better digester runability, better pulp strength and better bleachability. In addition, hardwood mills report a yield increase as a result of using the Lo-Solids cooking process (Table 1).

Table 1. Summary of mill Experience with Measured Yield Increases on Lo-Solids Cooking

Mill	Wood	Yield Increase	Method of Determination
A	Mixed So. US	4%	Wood Consumption Decrease (4 years)
B	Mixed No. US	4%	Wood Consumption Decrease (3 years)
C	Mixed So. US	2%	M-P Equation (3 studies)
D	Mixed So. US	1%	M-P Equation (2 studies)
E	Euca. So. America	2-3%	Black liquor Solids & M-P Equation
F	Mixed Ea. Canada	1.6%	Wood Consumption Decrease (2 years)
G	Birch Finland	1-2%	M-P Equation
H	Mixed So. US	2.4%	M-P Equation
I	Mixed No. US	1.5%	Wood Consumption Data
J	Euca. So. America	1.5%	Wood Consumption Decrease (2 years)
K	Birch Finland	3%	Wood Consumption Decrease (2 years)
L	Mixed Japan	2-3%	Short term trials
M	Euca. Spain	2-3%	Wood Consumption Decrease (3 years)
N	Mixed Japan	1.5-2.5%	Black Liquor Solids
O	Euca. So. America	3-4%	Black Liquor Solids
P	Birch Finland	3%	M-P Equation

This pulp yield improvement can be explained by several possible reasons: (i) Post-Impregnation Extraction (lower concentration of dissolved wood solids in cook zone); (ii) Low and even alkali concentrations; (iii) High sulfidity at the beginning of bulk delignification; (iv) Lower temperature.

In Lo-Solids cooking, the multiple white liquor additions and multiple black liquor extractions can be arranged in many different ways, depending on each individual digester. The inherent flexibility of the

Lo-Solids cooking allows for independent control of chemical reaction environments within the various zones of a continuous digester.

The objective of this research is to study the impact of cooking conditions of the various cooking zones on pulp yield and other parameters. For this research, two different studies were conducted using the laboratory counter-current Lo-Solids cooking process that consists four different cooking stages (Figure 1). In the first study, the impact of different alkali profiles on pulp quality at constant cooking temperature was investigated. Meanwhile, the impact of cooking temperature at given alkali profiles on pulp quality was investigated from the second study.

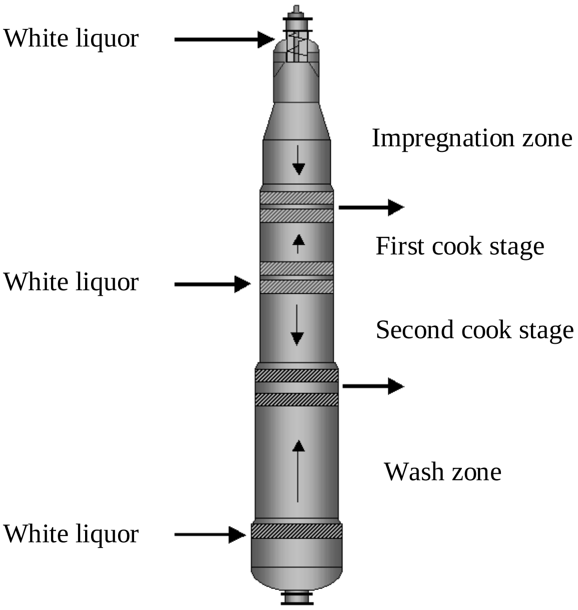

Figure 1. Lo-Solids cooking process with four different cooking zones

RESULTS AND DISCUSSION

Eucalyptus Urogandis chips from Brazil were used for both the first and second studies. For the first study, three sets of laboratory cooks using total effective alkali (EA) charges of 18, 20, 22, and 24% were conducted for producing various kappa number pulps.

In the first set of cooks, total EA charge was varied by varying the EA charge in the impregnation stage (8, 10, 12, and 14% EA) while adding the fixed EA charges at the first cook stage (6% EA) and wash zone (4% EA).

For the second set of cooks, the EA charge to the impregnation stage (8% EA) and wash zone (4% EA) were fixed and the first cook stage EA charges were varied (6, 8, 10, and 12% EA).

The third set of cooks was designed to vary the EA charge to the wash zone (4, 6, 8, and 10% EA) while adding a fixed EA charges to the impregnation (8% EA) and the first cook stage (6% EA). All cooks were done at 155 °C and 670 H-factor.

Pulping results from Lo-Solids cooks are summarized in Table 2.

Effect on Pulp Yield and Kappa Number

In order to compare pulp yield in terms of a degree of carbohydrate degradation without the influence of delignification rate, lignin-free yield was plotted as a function of total EA charges (Figure 2). In all three

Table 2. Pulping data for Lo-Solids cooks using multiple white liquor additions.

	Impregnation variable				**First cook variable**				**Wash zone variable**			
Total EA Charge (% on wood as NaOH)	18	20	22	24	18	20	22	24	18	20	22	24
Impregnation:												
EA Charge (% on wood as NaOH)	**8**	**10**	**12**	**14**	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**8**
Temperature (°C)	110	110	110	110	110	110	110	110	110	110	110	110
Liquor Sulfidity (% AA)	35.5	35.6	35.6	35.7	35.5	35.5	35.5	35.5	35.5	35.5	35.6	35.6
First cook												
EA Charge (% on wood NaOH)	**6**	**6**	**6**	**6**	**6**	**8**	**10**	**12**	**6**	**6**	**6**	**6**
Temperature (°C)	155	155	155	155	155	155	155	155	155	155	155	155
Liquor Sulfidity (% AA)	35.5	35.6	35.6	35.7	35.5	35.5	35.5	35.5	35.5	35.5	35.6	35.6
Residual EA (g/L NaOH)	5.2	8.8	10.9	14.7	5.2	8.5	11.8	14.5	5.2	5	5.4	6.2
Second cook												
Temperature (°C)	155	155	155	155	155	155	155	155	155	155	155	155
Wash zone												
EA Charge (% on wood NaOH)	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**6**	**8**	**10**
Temperature (°C)	155	155	155	155	155	155	155	155	155	155	155	155
Liquor Sulfidity (% AA)	35.5	35.6	35.6	35.7	35.5	35.5	35.5	35.5	35.5	35.5	35.6	35.6
Residual EA (g/L NaOH)	7.6	10.7	12.3	16.3	7.6	10.1	12.9	15	7.6	11.1	14.6	18.1
Final Cooking Results												
H-Factor	670	665	660	665	670	665	670	660	670	675	660	670
Kappa Number	18.6	15.6	14.9	13.7	18.6	16.2	15.1	14.4	18.6	18.4	17.1	16.3
Tappi Viscosity (mPa·s)	103.3	74.7	61.6	50.3	103.3	87.8	70.7	62.9	103.3	102.9	103.2	94.1
Scan Viscosity (dm3/kg)	1578	1445	1366	1283	1578	1512	1423	1375	1578	1577	1578	1540
Viscosity/Kappa number ratio	5.6	4.8	4.1	3.7	5.6	5.4	4.7	4.4	5.6	5.6	6.0	5.8
Hexuronoc Acid (meq/kg)	43	66.9	70.5	64.9	43	63	64.5	67.4	43	48.5	50	55.9
Total Yield (% on wood)	54.1	52.1	51.4	50.3	54.1	52.8	51.7	50.7	54.1	53.5	52.9	52
Lignin-free yield (% on wood)	52.6	50.9	50.3	49.3	52.6	51.5	50.6	49.6	52.6	52.1	51.6	50.8
Xylan content (% in pulp)	17.1	17.6	17.4	17.0	17.1	16.9	16.6	16.3	17.1	17.0	16.5	16.6
Glucan content (% in pulp)	82.1	81.9	82.1	82.6	82.1	82.4	82.7	83.2	82.1	82.3	82.7	83.0
Galactan content (% in pulp)	0.33	0.19	0.15	0.10	0.33	0.26	0.20	0.18	0.33	0.30	0.29	0.20
Mannan (% in pulp)	0.33	0.23	0.25	0.24	0.33	0.33	0.31	0.31	0.33	0.33	0.33	0.23
Hemicellulose content (% in pulp)	18.1	18.2	18.1	17.5	18.1	17.8	17.5	17.0	18.1	17.9	17.5	17.2
Cellulose content (% in pulp)	81.9	81.8	81.9	82.5	81.9	82.2	82.5	83.0	81.9	82.1	82.5	82.8

set of cooks, despite different white liquor profiles, lignin-free yield was found to decrease with increasing total EA charge. However, lignin-free yield obtained at a given EA charge depends on the white liquor profiles. A higher white liquor charge to the impregnation stage shows the most negative effect on lignin-free yield. Adding more white liquor to the 1st cook stage instead of the impregnation stage does not show any significant improvement. Increasing the percent split of white liquor to the 1st cook stage from 27% to 45% increases the lignin-free yield from 50.3 to 50.6%, by 0.3 units at a 22% EA charge. A similar trend is also observed at 20 and 24% EA charges. As compared to the 1st cook stage, increasing white liquor charge in the wash zone results in a substantial increase in lignin-free yield. This increase becomes larger with increasing percentage white liquor split to the wash zone. This result clearly indicates that adding more cooking chemical in the initial and bulk delignification stages increases carbohydrate degradation, especially cellulose degradation (Figure 3). Adding more alkali charge to the impregnation stage shows over 1.5% and 0.5% lower cellulose yield at 24% EA charge than a higher alkali charge in the wash zone and 1st cook stage, respectively. Meanwhile, all three different alkali profiles show a similar xylan yield (Figure 4). This means that lignin-free yield depends mainly on the cellulose yield. Similar results from another hardwood study are reported by Achren and Stromberg (3, 4).

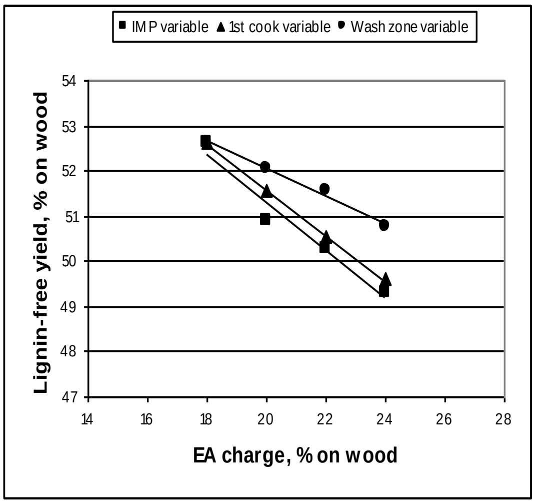

Figure 2. Impact of alkali profile on lignin-free yield

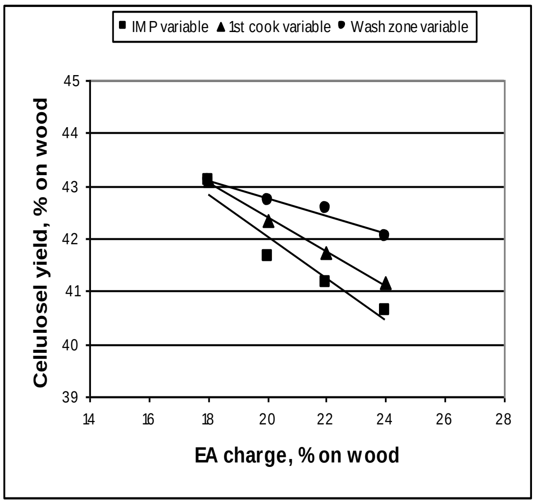

Figure 3. Impact of alkali profile on cellulose yield

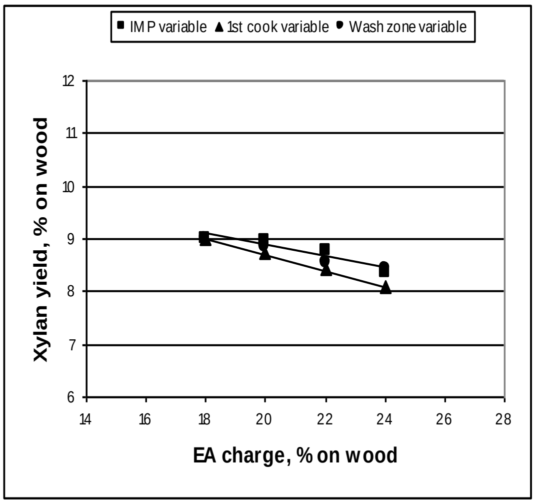

Figure 4. Impact of alkali profile on xylan yield

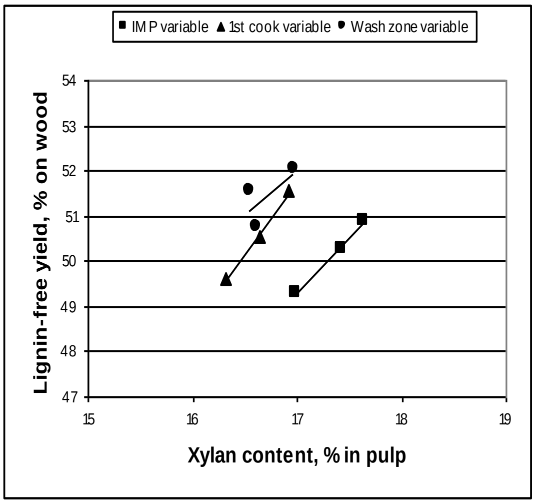

Figure 5. Impact of xylan content on lignin-free yield

Another interesting finding from these cooks is that xylan content in pulp used as the indicator of pulp yield variation for a conventional cooking process can no longer be used for yield prediction for the modified cooking system using alkali profiles (Figure 5). At the same xylan content of 17% in the pulp, the first set of cooks (increasing the white liquor charge to the impregnation stage) shows over 2% lower lignin-free yield than the third set of cooks (increasing white liquor charge to the wash zone). Figure 5 clearly also indicates that the variation of xylan content does not reflect the variation of lignin-free yield, even from the same alkali profile cook.

Because the cooking conditions are mainly controlled by the target kappa number, the impact of alkali profiling on pulp yield should be compared at a given kappa number. When total yield is plotted against kappa number (Figure 6), increasing the white liquor charge in the wash zone shows the most negative effect on pulp yield at a given kappa number. This result is completely opposite compared to the results from Figure 2. This negative effect on pulp yield at a given kappa number can be explained by lower delignification rate. As seen in Figure 7, alkali profile has quite a different influence on the delignification compared to pulp yield. Adding more white liquor to the wash zone (increases the percent split of white liquor from 22% up to 42%) leads to higher kappa number at a given EA charge. This indicates that for better delignification, white liquor charge should be higher in the initial or bulk delignification stages. Due to the lower delignification rate, alkali profile in the wash zone requires 4% higher EA charge in order to obtain the same kappa number of 16 than alkali profile in the impregnation and 1st cook stages. This higher alkali charge in the wash zone results in lowering total yield.

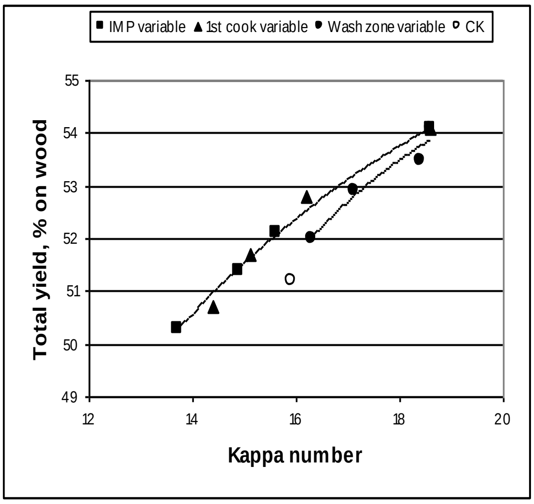

Figure 6. Impact of alkali profile on total yield as a function of kappa number

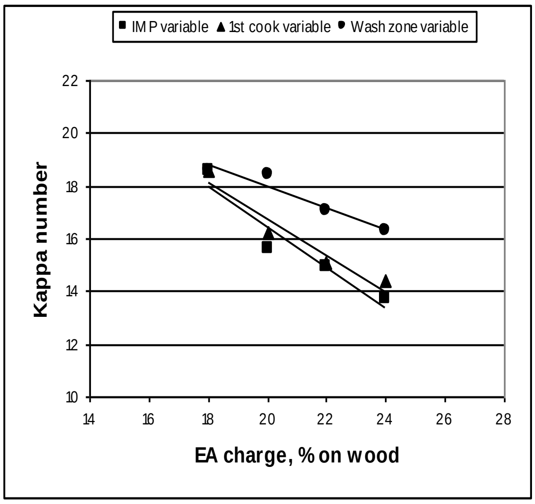

Figure 7. Impact of alkali profile on kappa number as a function of EA charge

This study also confirms the yield benefit from Lo-Solids mills. As compared to the conventional laboratory cook, Lo-Solids cooking shows a higher total yield at a given kappa number (Figure 6).

For study 2, the impact of cooking temperature on pulp yield was also studied at a constant H-factor of 700. The same total EA charges and white liquor profiles as the first (adding more alkali to the impregnation stage) and second (increasing alkali charge in the 1st cook stage) sets of cooks from the previous studies are used for this study.

When total yield is plotted against kappa number (Figure 8), results clearly demonstrate that at a given kappa number, the same total yield was obtained from three different cooking temperatures regardless of different alkali profiles. In other words, higher cooking temperature does not show any negative impact on pulp yield compared to lower temperature. As shown in Figure 9, the only cooking parameter that shows a good correlation with total yield is the black liquor EA concentration at the end of the 2nd cook stage at a given H-factor. This correlation exists regardless of cooking temperature or the different alkali profiles. Pulp yield decreases by increasing the target EA concentration at the end of the 2nd cook stage (the end of bulk delignification).

Compared to other cooking parameters, the EA concentration at the end of 2nd cook stage also correlates well with kappa number (Figure 10). However, it shows a non-linear relationship. As the black liquor EA concentration increases from 1 g/l to 6 g/l EA as NaOH, the kappa number decreases from 21 to 15 and then levels off above 6g/l EA concentration without a significant kappa number reduction (1 kappa unit change by increasing from 6 to 12 g/l EA). In other words, an excess white liquor charge prior to the 2nd cook stage does not contribute to further reduction in kappa number. Instead, this excess white liquor charge will negatively affect the pulp yield.

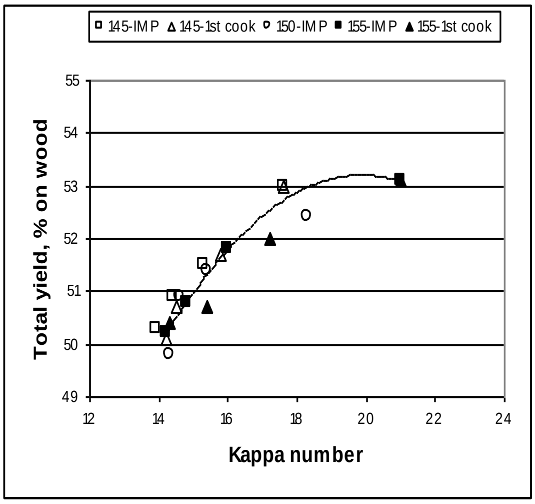

Figure 8. Impact of cooking temperature on total yield as a function of kappa number

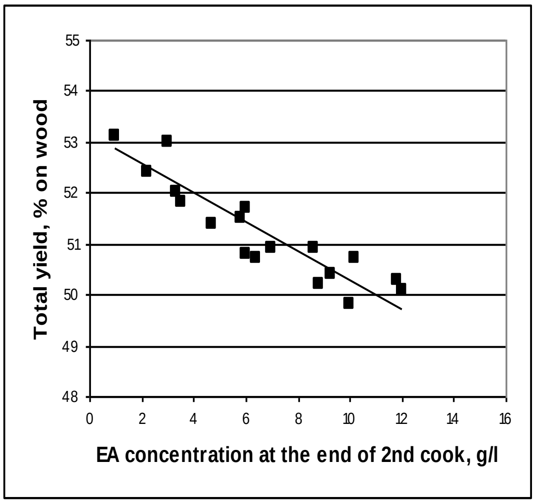

Figure 9. Impact of EA concentration at the end of 2nd cook stage on total yield

In order to maintain a higher pulp yield, the EA concentration at the end of 2nd cook stage should be lowered by decreasing the white liquor charge. However, this lower concentration also increases the kappa number. Since H-factor is used for kappa number control, the impact of H-factor on pulp yield at a given kappa number was investigated. For this study, H-factor was increased from 700 to 1000. This increase was obtained by increasing the cooking time only in the wash zone. As compared to 700 H-factor at 145°C cooking temperature, the overall cooking time for 1000 H-factor at 155°C is still shorter. Results in Figure 11 clearly demonstrate that an increase in H-factor at higher cooking temperature shows a positive effect on the pulp yield. At a total white liquor charge of 18% EA on O.D. wood, 1000 H-factor

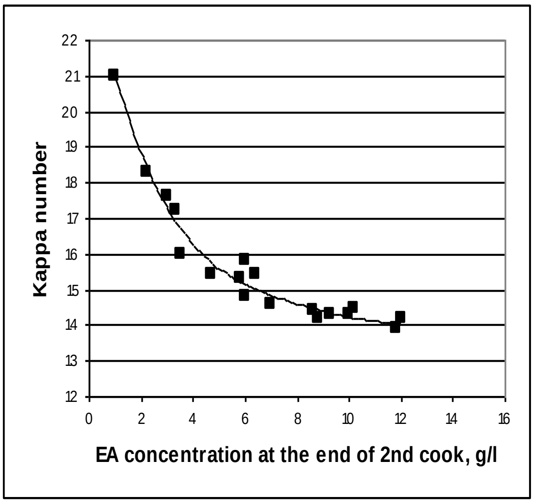

Figure 10. Impact of EA concentration at the end of 2nd cook stage on kappa number

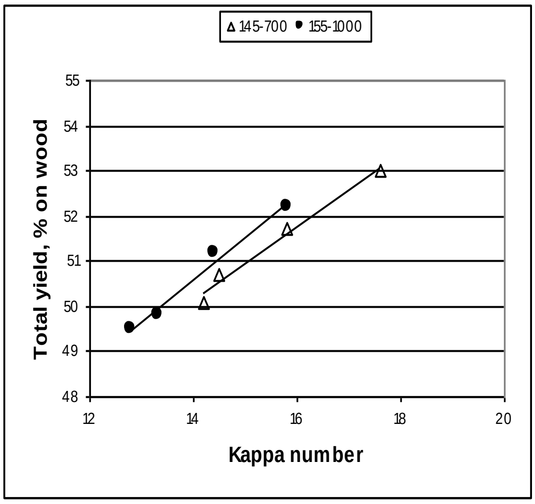

Figure 11. Impact of H-factor on total yield at different cooking temperatures

at 155°C produces 16 kappa pulp. The same 16 kappa number pulp is produced from a 20% EA charge at 700 H-factor and 145°C. This means that increasing H-factor at higher cooking temperature without increasing cooking time results in a reduction of white liquor charge. This lower alkali charge increases total pulp yield by 0.5% units at a given kappa number due to the lower EA concentration during the bulk phase. At the same cooking temperature of 155°C, a longer retention time in the wash zone by increasing the H-factor does not show any negative impact on pulp yield (Figure 12). A 1000 H-factor shows more than 0.5% units higher total yield compared to a 700 H-factor. However, increasing H-factor at the same cooking temperature requires a longer overall cooking time which is not practical in a mill at a given production rate.

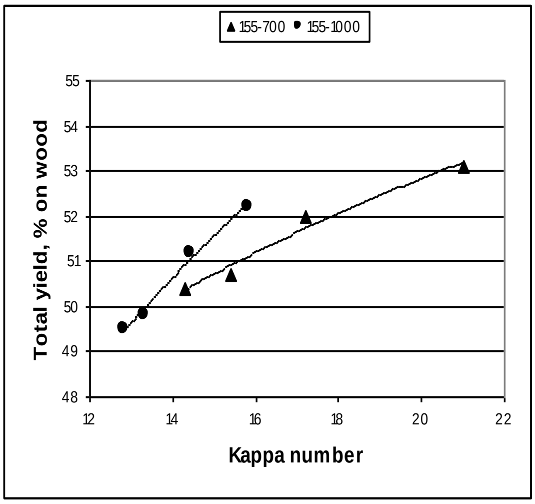

Figure 12. Impact of H-factor on total yield at the same cooking temperature

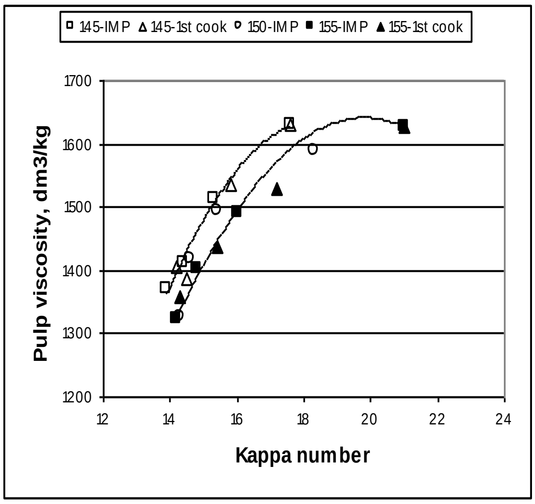

Figure 13. Impact of cooking temperature on pulp viscosity as a function of kappa number

Effect on Pulp Viscosity and HexA

When pulp viscosity is plotted as a function of kappa number, a higher cooking temperature shows a negative impact on pulp viscosity at a given kappa number (Figure 13). At a kappa range from 14 to 18, the lower cooking temperature of 145°C shows 50 to 60 dm^3/kg units higher pulp viscosity than pulp produced at cooking at temperature of 155°C. At the same cooking temperature, alkali profiles do not affect the pulp viscosity. These results indicate that the cooking parameters affecting the pulp viscosity are different from that affecting pulp yield.

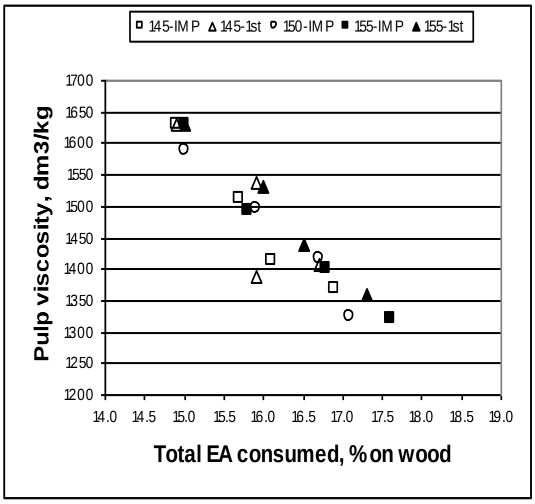

Figure 14. Linear relationship between pulp viscosity and total EA consumed

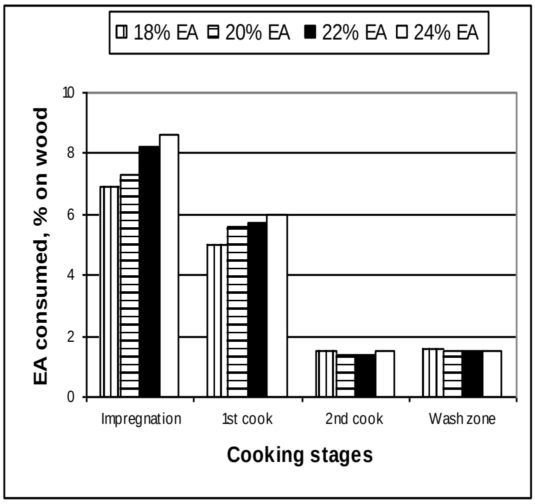

Figure 15. EA consumption with alkali profile in the impregnation stage at 155°C

Despite different cooking temperature and alkali profiles, total EA consumption during cooking shows a linear correlation with pulp viscosity (Figure 14). The pulp viscosity is determined by overall cooking chemical consumption, not by any specific cooking stage chemical consumption. When total EA consumption is increased by 0.5 units, pulp viscosity decreases by more than 50 units. As shown in Figure 15 and 16, more than 88% of the cooking chemical is consumed in the Impregnation, 1st cook and 2nd cook stages (more than 75% in both impregnation and 1st cook stages). In these cooking stages, cooking chemical consumption increases with increasing the cooking chemical charges at a given cooking temperature. In other words, increasing cooking chemical charges at the initial and bulk delignification stages results in a significant pulp viscosity loss.

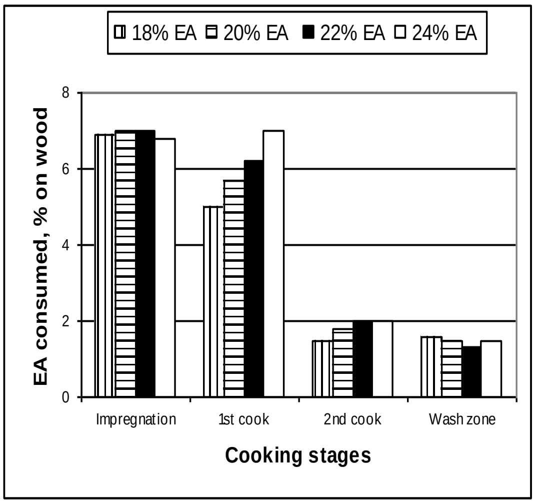

Figure 16. EA consumption with alkali profile in the 1st cook stage at 155°C

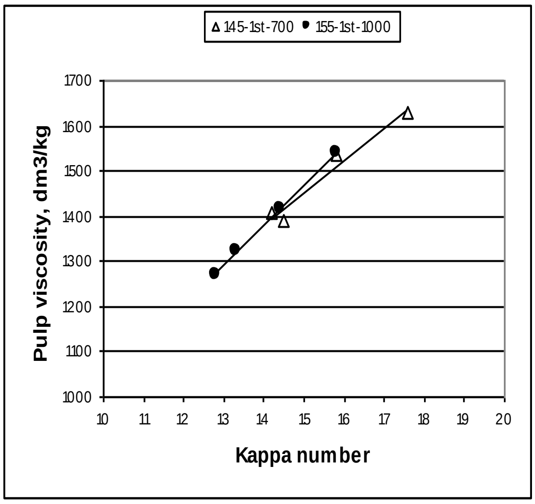

Figure 17. Impact of H-factor on pulp viscosity at two different cooking temperatures

Since a higher alkali charge in the initial or bulk delignification stages shows a negative impact on pulp viscosity due to the higher EA consumption, the impact of H-factor on pulp viscosity at a given kappa number was investigated. Under the same alkali profile in the 1st cook stage, a cooking temperature of 155°C at 1000 H-factor shows the similar pulp viscosities at a given kappa number as 145°C at 700 H-factor (Figure 17). In order to obtain the target 16 kappa number, 1000 H-factor cook at 155°C requires 2% EA units lower whiter liquor charge than 700 H-factor at 145°C. This result clearly indicates that the reduction of white liquor charge offsets the negative influence of a higher cooking temperature even with increased cooking time, which results in maintaining the same pulping selectivity (Viscosity/kappa ratio) as cooking at a lower temperature.

The formation of Hexenuronic acid (HexA) during alkaline pulping is one of the important research subjects due to its effect on bleaching operations. However, most of HexA formation studies have been done using the conventional cooking method, which is a cook without white liquor profiling and black liquor removal from digester during the cooking. For the new modified continuous cooking technology, it is necessary to study the effect of cooking conditions on HexA formation during the cooking with multi white liquor additions and black liquor extractions.

When the kappa number is varied by varying cooking chemical charge (EA charge) at a constant H-factor, HexA content of the pulp was found to increase with decreasing kappa number regardless of the cooking temperature (Figure 18). The only cooking parameter showing a correlation with HexA formation is the black liquor EA concentration in the end of 2nd cook stage (Figure 19).

When the EA concentration increases from 1g/l to 6g/l, HexA content of the pulp increases from 28 to 57 meq/kg and tends to level off with increasing EA concentration above 6g/l. Based on this result, HexA formation during the cook can be controlled by adjusting the EA concentration at the end of the 2nd cook stage. In order to obtain a lower HexA content in the pulp, the EA concentration of the 2nd cook should be maintained at a lower level. As previously discussed, EA concentration above 6g/l at the end of this cooking stage (the end of bulk delignification) not only levels off the kappa number but also increases the HexA content in the pulp.

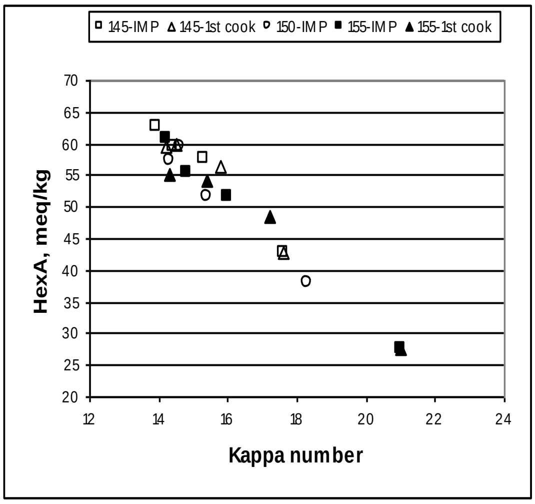

Figure 18. Effect of cooking temperature and alkali profiles on HexA as a function of kappa Number

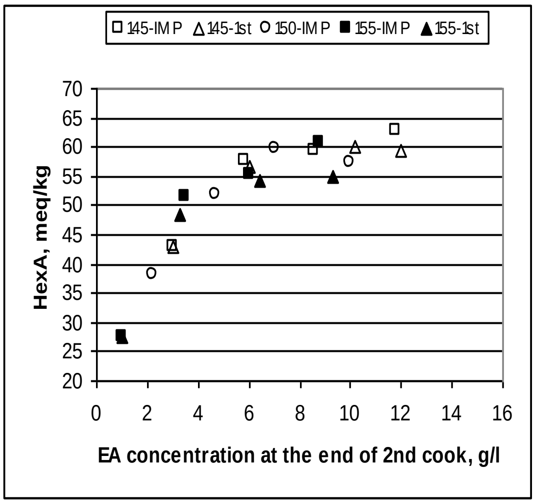

Figure 19. Effect of EA concentration at the end of 2nd cook stage on HexA

Because HexA formation originates from Xylan, the relationship of HexA and xylan content in the fiber was studied and is shown in Figure 20. There is no correlation found between HexA and xylan content in the fiber. When xylan content is higher than 15.6% on lignin-free pulp, a wide range of HexA content is obtained at similar xylan content. Below 15.6%, HexA content of the fiber does not vary with varying xylan content. In other words, the HexA content of the fiber is independent of the xylan content.

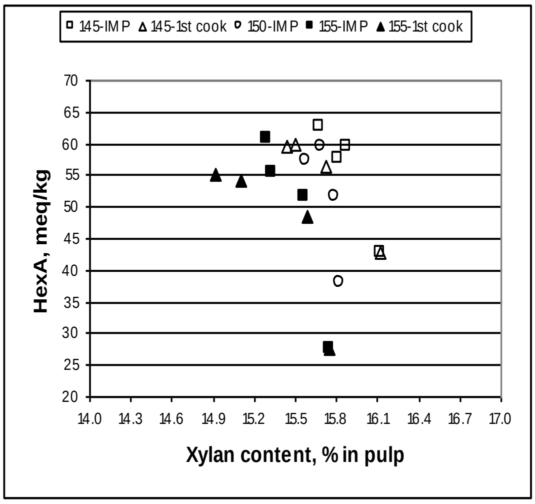

Figure 20. Relationship between HexA and xylan content in pulp

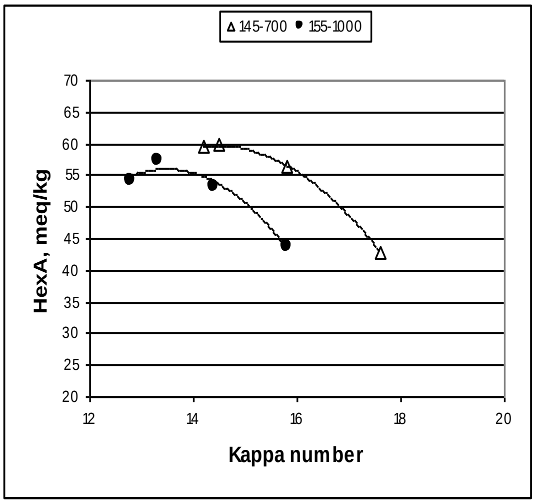

Figure 21. Impact of H-factor on HexA content at two different cooking temperatures

As discussed previously, a higher H-factor cook at a higher temperature has a positive impact on pulp yield and viscosity. From the same cooks, the impact of H-factor on HexA content was investigated. The results in Figure 21 clearly demonstrate that the lower HexA content can be obtained at a given kappa number when a cook is carried out with a higher H-factor. At a 16 kappa umber, 1000 H-factor cook at 155°C shows 10 meq/kg units lower HexA content than 700 H-factor cook at 145°C.

CONCLUSIONS

1. As compared to conventional cooking, multiple white liquor additions show a higher pulp yield.
2. Pulp yield depends mainly on cellulose yield, and cellulose yield is significantly affected by alkali profiles.
3. Higher alkali charge in the wash zone shows lower pulp yield at a given kappa number.
4. Xylan content in pulp does not show any correlation with pulp yield.
5. At a constant H-factor, increasing cooking temperature does not show any negative effect on pulp yield regardless of alkali profiles.
6. Effective alkali concentration at the end of 2nd cook stage shows a good correlation with pulp yield and kappa number regardless of cooking temperature and alkali profile.
7. A higher H-factor cook at a higher temperature with a shorter cooking time shows a higher pulp yield at a given kappa number than a lower H-factor cook at a lower temperature with a longer cooking time.
8. Pulp viscosity is determined by total EA consumption, not by any specific cooking stage EA consumption.
9. At a constant H-factor, increasing cooking temperature shows a negative effect on pulp viscosity at a given kappa number.
10. Due to a lower alkali charge, a cook at a higher temperature with a higher H-factor shows the same the pulp viscosity at a given kappa number as a cook at a lower temperature with a lower H-factor.
11. HexA content of the pulp correlates only with alkali concentration at the end of the 2nd cook zone. HexA content increases with increasing an alkali concentration.
12. Xylan content of pulp does not show any correlation with HexA content.
13. Pulp produced at a higher cooking temperature with a higher H-factor shows lower HexA content at a given kappa number compared to a lower cooking temperature with a lower H-factor.

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