Application of pulping models to investigate the performance of commercial continuous digesters

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ABSTRACT: Continuous digesters are complex plug flow reactors with long residence times. The complexity makes it difficult to develop realistic pictures of their operating characteristics. One relatively simple method to study digester performance is to develop a simulation of the reactor and use it to test various operating scenarios. In this study, we developed a pulping model to look at the operation of a continuous commercial digester operated in EMCC™ and LoSolids™ cook modes. The model tested well and served to investigate some operational issues. We found that we could modify the white liquor feed split to achieve an optimal kappa profile through the digester and improve pulping uniformity. More white liquor to the front of the digester results in less pulping being required in the wash zone and in better pulping uniformity. Improvements to the white liquor feed split also allow the digester to pulp thicker chips without adversely affecting pulp uniformity. Pulp uniformity and the benefits of balancing delignification through the various digester zones should be considerations when deciding what white liquor split to use. Overthick chips have a moderate affect on pulp uniformity. Turning off the slicer did not appear to significantly affect pulp uniformity for the mill used in this study.

Application: Modeling allows mills to efficiently and economically simulate and modify digester operations.

Kamyr digesters are complex plug flow reactors with long residence times. The complexity makes it difficult to develop realistic pictures of their operating characteristics. Performing experiments to study digester operations can be expensive, especially if they cause off-grade pulp production, and difficult to run because of the long residence times and problems associated with keeping the digester at a steady state. These long residence times also make digester kappa control challenging.

One relatively simple method to study digester performance is to develop a simulation of the reactor and then exercise that simulation through various operating scenarios. If the simulator is reasonably accurate, the results will provide a meaningful picture of the digester operation and insights into how the mill might modify digester operations to improve performance. Various investigators have used pulping models to study the operation and control of continuous digesters. Miyanishi and Shimada have published a review of the application of digester models [1].

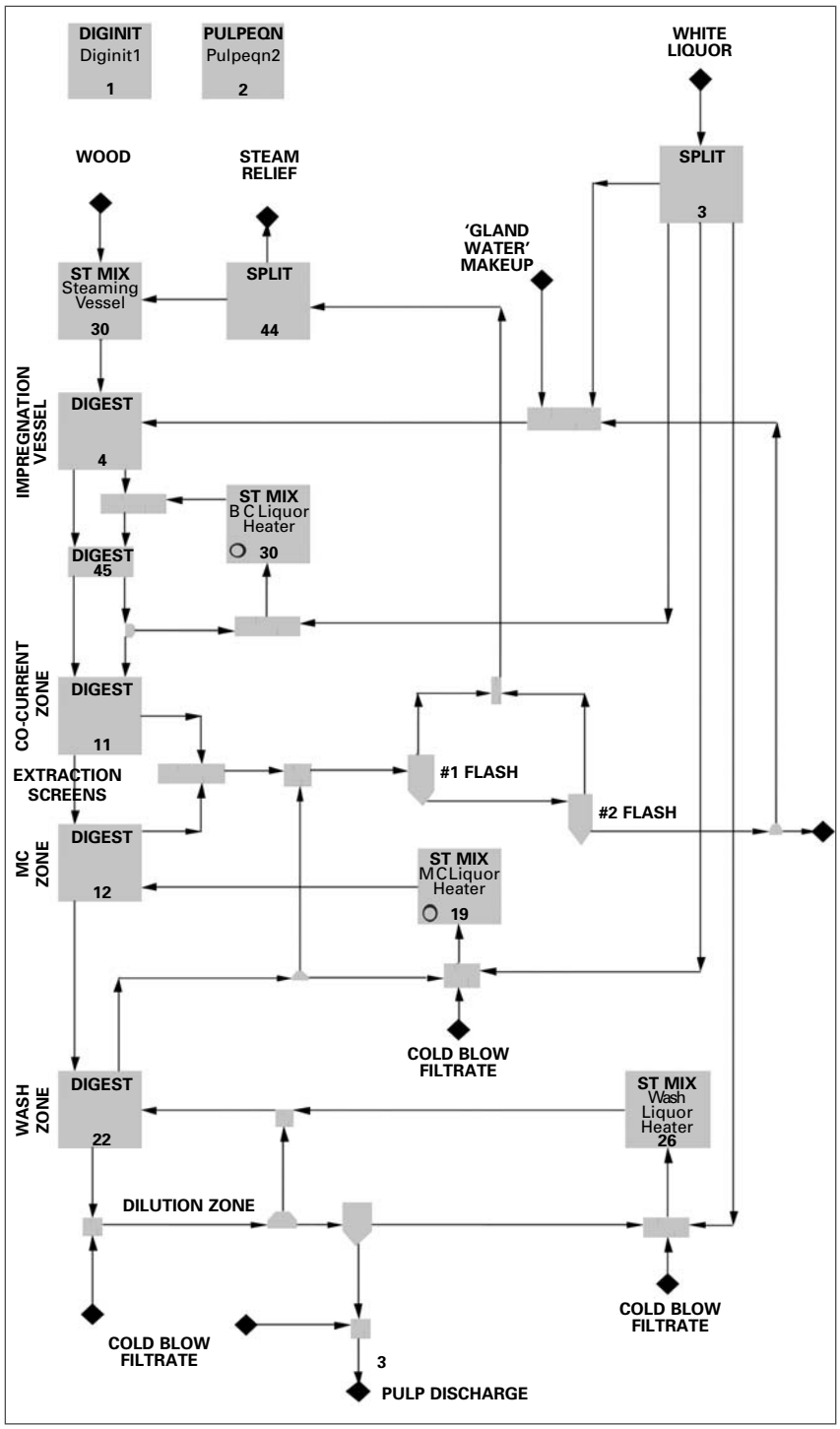
The digester model developed at the University of Washington has shown its ability to predict accurately pulping results through several pulping studies [2-4]. The model solves the reaction diffusion equations that describe the pulping behavior within a wood chip. It can predict pulp properties such as kappa, yield, and viscosity and liquor properties such as residual effective alkali and total dissolved solids. It also can predict the uniformity, i.e. kappa distribution, of a pulp that results from having a finite chip size distribution or other non-ideal conditions. The model runs as a block in the WinGEMS™ program. This permits straightforward simulation of complicated digester configurations such as LoSolids™ Kamyr digesters. By configuring the DIGEST block with various SPLIT, MIX, and HEATX blocks, the program can simulate any digester configuration. Arasakesari and Gustafson previously described the WinGEMS™ pulping blocks [4].

This pulping model has predicted the performance in a Kamyr digester with some success [4]. This previous work, however, was not a detailed study and was designed more to show potential applications of the model. The objective of the current work is to develop a more complete simulation of an operating Kamyr digester, assess the accuracy of the simulation under typical operating conditions, and use the model to investigate the effect of various operational issues on digester performance.

The Kamyr digester studied is in a Pacific Northwest mill that pulps both hardwoods and softwoods. We concentrated our modeling effort on the softwood pulping, as the digester was more stable in these campaigns and the softwood kinetics are better understood. The digester is a two vessel reactor manufactured by Ahlstrom. It can run in an EMCC™ mode or in a modified LoSolids™ pulping mode.

Model development and assessment

We assembled WinGEMS™ blocks to model the digester system. **Figure 1** shows a simplified representation of the digester simulation. The path of the chips in the model follows their path in the digester. The model presteams the wood in a STMIX block followed by pulping in various DIGEST blocks. In the actual simulation, each digester zone uses one or more DIGEST blocks to produce a more accurate representation of the digester conditions. We simulated the wash zone, for example, with three counter-current DIGEST blocks. Surrounding each of the DIGEST blocks are STMIX, MIX, and SPLIT blocks to handle the liquor recycles associated with the digester. To accurately model, or control, a digester, the compaction or packing density in each region of the digester must be known.



1. Simplified representation of the digester simulation.

Compaction of the chip column is important because it affects the residence time in a given zone. In developing the digester model, we assumed that the wood compaction in each zone is similar to that presented by Harkonnen [5]. The wood volume fraction for each zone used in the model is shown in **Table I**. A zone's packing density, which is input to the model, can be calculated from the wood density and the wood volume fraction. The residence time in a given zone is calculated by the model using the wood mass flow rate, the volume of a digester segment, and the zone's packing density.

After developing the model, we assessed its accuracy against mill data. **Table II** shows the chip size distribution typical for the mill input to the digester. For our simulations, we combined the Pan and Pin chips into one fraction resulting in the model chip size distribution, also shown in Table II. A study by the mill provided the approximate lengths and thicknesses for the chips in each size fraction.

Wash filtrate alkali concentration is important (as will be discussed later), especially when pulping in the LoSolids™ mode. Limited data existed for the residual alkali in the wash filtrate. To obtain values for the wash filtrate alkalinity, we developed a rough correlation relating wash filtrate alkali concentration and liquor conductivity. Liquor conductivity is continuously measured online. This correlation is shown in Eqn. (1)

$$EA(g/L) = 0.1*C - 0.5 \quad (1)$$

where EA is the effective alkali in g sodium oxide (Na_2O)/L, and C is conductivity in mhos. We calculated wash filtrate EA from operating data conductivities using Eqn. 1 and input to the model.

The mill normally operates in a modified cross flow LoSolids™ cook mode, adding cold blow filtrate only to the MC circulation system. In this model, we added 230 gal/min of cold blow filtrate to the MC zone. To maintain hydraulic balance in the MC zone, the model extracts 342 gal/min from the flow before the cold blow addition. The extra amount extracted is equivalent to the white liquor flow to the zone.

For validation, we chose the best LoSolids™ run based on how close it approached steady-state. Criteria such as consistent production rate, and kappa stability determined the best operating period. **Table III** shows the model inputs and **Table IV** the simulation results for the validation study.

The chip moisture in Table III appears to be low, but the summer was long and warm, resulting in dry chips which persisted into the fall. We weighted the white liquor split for this LoSolids™ run heavily toward the front end of the pulping. Based on a mass balance, there is more water output than input to the system. Pulping reactions generate some water. Some water also leaks into the system as gland water. To complete the mass balance, we added an assumed 100 gal/min of water to the impregnation white liquor.

Table IV shows that the model predicts the operation of the digester well. The liquor flows and temperatures are all reasonably accurate. The only temperature that is significantly different from the actual is for the blow line. This temperature is hard to predict because of the non-ideal mixing in the dilution zone at the bottom of the digester. Errors in this temperature are unimportant, however, from a pulping kinetics standpoint. The

ZONE	WOOD VOLUME FRACTION, e
Chip pile trim screens	0.50
Trim screens - extraction	0.70
MC zone	0.70
Wash I	0.65
Wash II	0.60
Wash III	0.55

I. Volume fractions in each digester zone.

	TYPICAL MILL CHIPS		MODEL DISTRIBUTION		
	SIZE (mm)	%WT. DIST.	THICK (mm)	LENGTH (mm)	%WT. DIST.
Pan	<3	0.9	–	–	–
Pins	3 - 7	14.1	3.0	15	15.0
Accepts	7	79.2	4.5	20	79.2
Overthick	>8	5.8	9.0	25	5.8

II. Chip size distributions used in simulations.

model was also successful at predicting the generation of black liquor solids as well as average kappa. The yield prediction is probably somewhat high. We could easily tune this, however, if yield data from the mill were available. (The "actual" yield of the mill is also an estimate, which is also probably higher than the actual yield). Note that the kinetics used in simulating the digester were the standard softwood kinetics in the DIGEST block. No model tuning was required to get the accurate results shown in Table IV. The softwood kinetics in the DIGEST block appear to be valid. The challenge in modeling a commercial continuous digester is to develop an accurate input data set for the digester operating conditions.

Given the success of the model in predicting general pulping results, it is reasonable to assume that the model predicts accurately the changes in the wood composition as the chips flow through the digester. **Table V** reviews profiles of important variables in a cook.

Little delignification is completed in the impregnation vessel, but the wood still loses over 20% of its mass through carbohydrate and acetyl neutralization reactions. The kappa actually increases because the initial part of the cook removes more carbohydrates than lignin. The co-current and MC zones account for about 90% of the pulping with the remaining 10% occurring in the wash zone. It is generally desirable to keep the amount of pulping done in the wash zone to a modest amount, as this zone is the most difficult to control and keep under steady state. The alkali profile through the pulping appears to be good. While the initial part of the cook has a somewhat high alkalinity, the EA concentrations remains fairly constant all the way through the bulk and residual delignification phases. At no time does the alkali concentration approach zero, which would be detrimental to the pulp quality and bleachability.

The pulping model has the ability to estimate the pulp uniformity. **Figure 2** shows the predicted kappa distribution for a LoSolids™ cook. Based on the results, the digester should produce a uniform pulp. Only 2% of the fibers have a kappa above 35 and virtually none have a kappa above 90. The alkali split and cool pulping temperatures employed by the continuous digester help the pulp be uniform even when there is a considerable fraction (6%) of over sized chips.

We also developed a model of the digester running in the EMCC™ mode and tested it against operating data. The operation in this mode was not as stable as in the LoSolids™ pulping as the digester had newly started up. **Table VI** shows the results of the simulations. In general, the model predicted the pulping results reasonably well. The variability in the operation at that time makes any definitive modeling effort difficult. As in the low solids case, no tuning of the pulping kinetics was required to predict the pulp kappa.

Case studies

The simulation results shown above demonstrate that the model does a reasonable job of predicting the operation of the Kamyr digester. We next used the model to investigate some operational issues that were of concern to the mill and presumably other mills operating Kamyr digesters.

White liquor splits

Mills can modify the alkali profile in modern continuous digesters by changing the total EA charge and by changing the white liquor split between the different zones. Splitting the white liquor in different ways will affect pulp quality and the overall pulping kinetics. It will also have a profound affect on pulp uniformity, which presumably will influence bleachability and pulp performance. The pulping model used in this work is uniquely qualified to investigate the relationship between the digester liquor profiles and pulp uniformity.

To investigate this relationship we used the LoSolids™ simulation with the chip thickness distribution in Table II and the pulping conditions in Table III, except we varied the white liquor split. We studied 16 liquor-split configurations (see **Table VII**).

Figure 3 shows the digester kappa profiles for two of the studies. These results bound the results from the other

			Flow (gal/min)	Model	Actual	Stdev	%COV
Chip feed	170.7	tons/h	Gland water	100	–	–	–
Moisture	35.3	%	Cold blow	2087	2087	157.3	7.5
Ea charge	17	%	CB to MC	230	230	7.5	3.3
Sulfidity	25.18	%	BC circ.	6177	6173	215	3.5
White liquor	891.8	gal/min	Wash circ.	845	845	146	17.3
%WL split	71.1	IV	–	–	–	–	–
	3.7	BC	Temps (°C)	Model	Actual	Stdev	%cov
	12.1	MC	BC hot	163.5	162.6	0.9	0.5
	13.1	Wash	MC hot	157.3	157.3	0.9	0.6
Cold blow EA	2.5	g/L	Wash hot	157.1	157.1	0.9	0.5
	–	–					

III. Model inputs for LoSolids™ pulping simulation.

FLOWS (gal/min)	MODEL	ACTUAL	STDEV	%COV
MC	1319	1314	47	3.6
Blow	1999	2001	91	4.5
Weak black liquor	1946	1979	271	13.7
TEMPS (°C)	**MODEL**	**ACTUAL**	**STDEV**	**%COV**
Impregnation	132.8	–	–	–
Upper extraction	160.2	160.4	1.0	0.6
Lower extraction	160.2	158.9	1.2	0.7
MC cold	158.5	157.3	2.3	1.4
Blow "A" temp	103.5	89.5	3.8	4.3
	MODEL	**ACTUAL**	**STDEV**	**%COV**
% BL solids	18.6	19.3	0.67	0.0
Yield	45.1	47.3	–	–
Kappa	21.2	20.3	1.6	7.9

IV. Model outputs for LoSolids™ pulping simulation.

	L/W (L/kg)	RES OH M/L	H-FACTOR	KAPPA 181.4*	YIELD
IV	2.9	0.6	21.1	191.5	77.4
Co-current	3.3	0.14	598.7	99.7	56.9
MC	5.0	0.2	763.4	42.0	48.9
Wash	4.5	0.23	798.6	21.2	45.1
Total	–	–	**2182**	–	–

* Kappa number of uncooked wood

V. Modeled profile information through a LoSolids™ cook.

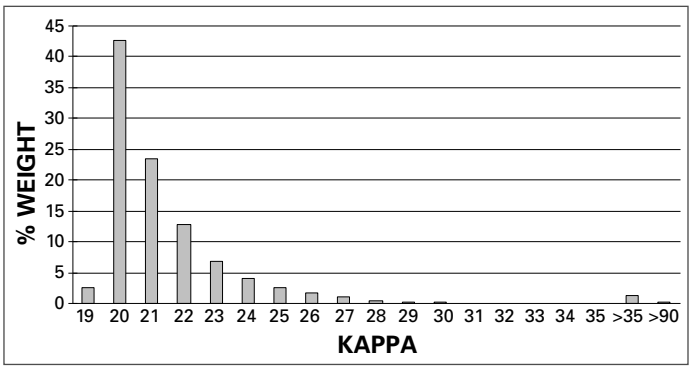
FLOWS (gal/min)	MODEL	ACTUAL	STDEV	%COV
MC	1420	1417	35	2.5
Blow	1710	1738	108	6.2
Weak black liquor	1828	1809	128	7.1
TEMPS (°C)	**MODEL**	**ACTUAL**	**STDEV**	**%COV**
Impregnation	132.6	–	–	–
Upper extraction	159.3	158.6	0.9	0.5
Lower extraction	158.3	156.3	0.9	0.5
MC cold	157.6	155.4	1.6	1.0
Blow "A" temp	108.6	97.9	4.6	4.7
	MODEL	**ACTUAL**	**STDEV**	**%COV**
% BL solids	17.5	17.9	0.16	0.0
Yield	45.5	47.1	–	–
Production	1075	1113	26.2	2.4
Kappa	23.6	21.5	3.9	18.1

VI. Model outputs for EMCC™ pulping simulation.

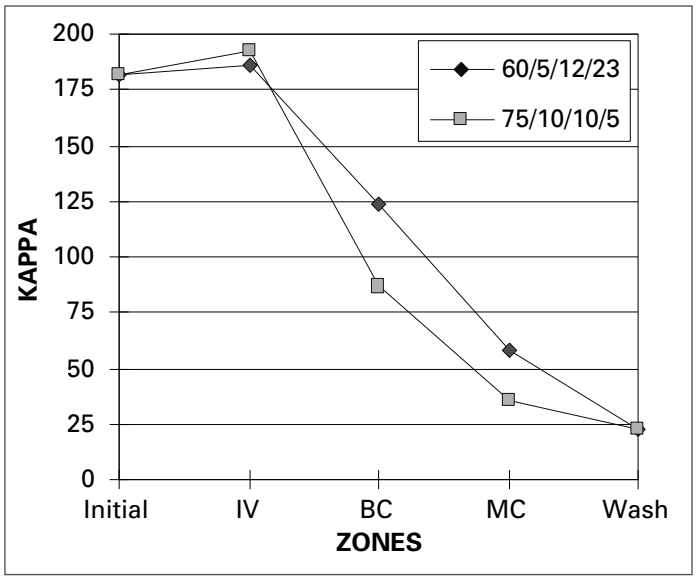
IV	BC	MC	WASH	IV	BC	MC	WASH
60	5	12	23	65	10	17	8
60	5	17	18	70	5	7	18
60	5	22	13	70	5	12	13
60	10	17	13	70	10	7	13
60	15	12	13	70	10	12	8
65	5	12	18	75	0	12	13
65	5	17	13	75	5	5	15
65	10	12	13	75	10	10	5

VII. %White liquor feed splits.

profile studies and serve as representative examples of how splitting white liquor will affect digester performance. The figure demonstrates that when the same liquor charge is split differently, cooking across the zones is affected. While the two runs have essentially the same final kappa, 22.6 for the 60/5/12/23 split and 22.4 for the 75/10/10/5 split, the cook profile is different.



2. LoSolids™ model kappa distribution.



3. Kappa profiles for two liquor splits (See Table VII).

In the 60/5/12/23 case, less pulping was accomplished in the top of the digester compared to the 75/10/10/5 split. Since we added less liquor to the impregnation vessel (IV) in the 60/5/12/23 run, the residual alkali concentration of the IV zone is low. Minimal white liquor is added to the BC circulation loop, therefore the free liquor alkali concentration to the co-current zone is also low. This will result in slow pulping through the co-current zone and more cooking required in latter stages, especially the wash zone. For the 60/5/12/23 split, the wash zone needed to cook from a kappa of 59 where in the 75/10/10/5 run, the average kappa entering the wash zone was only 35. Taking a large kappa drop in the wash zone may be troublesome as this zone is often difficult to control and keep at a steady state with regard to liquor flows and temperature.

We can better understand the role of alkali depletion by examining the alkali profile across the thickest chip from zone to zone. **Figures 4 and 5** show the alkali concentration at the center of the thickest chip (9mm) and the bulk alkali concentration as the chip moves down the digester.

For the 60/5/12/23 run, the chip center does not contain any alkali until the wash zone. Therefore, it endured at least 1650 Hfactor before alkali was present at the chip center. Depletion of alkali can lead to carbohydrate degradation and lignin precipitation onto the fibers. In addition, Fig. 4 shows that the alkali at the end of the cook is quite high, over 0.5 M [20 g sodium hydroxide (NaOH)/L]). Such high final alkali concentrations may diminish the amount of redeposited xylans on the fiber and hence lower pulping yields. If pulping hardwoods, this would be an even larger effect due to the hardwood's high xylan content.

The other liquor split (75/10/10/5) provided sufficient alkali to maintain diffusion into the chips to replenish the alkali consumed in pulping reactions. The thickest chip center received alkali by the co-current cook zone and was able to delignify the center through most of the cook. The final alkali concentration for this cook was a more reasonable 0.2 M (8 g NaOH/L).

The alkali profile through the chip for the 75/10/10/5-liquor split resulted in improved kappa uniformity. **Figure 6** shows the kappa uniformity for both simulations. For both simulations, the average kappa was the same, but the pulp resulting from the 60/5/12/23 split is more non-uniform. It contains significant amounts of overcooked (low kappa) and undercooked (high kappa) pulp, which may result in low pulp strength, high rejects, and increased bleach chemical demand. For the same liquor charge but different white liquor split, the 75/10/10/5 cooking produced a uniform pulp with very little over- or undercooked wood. Such a pulp may have better strength, a higher screened yield, and better bleaching performance.

The results of these simulations show that different white liquor splits can lead to quite different pulping behavior, even when the same final kappa is achieved. Different liquor splits allow adjustment of where the major kappa reductions take place to improve digester operation and control. The liquor splits also have a large impact on pulp uniformity, which may affect pulp quality. By adjusting the liquor split, the uniformity of the pulp may be improved. If there is a desire to increase the chip size in the digester, to improve liquor percolation for example, the liquor split may be adjusted to maintain pulp uniformity in the face of the large chips.

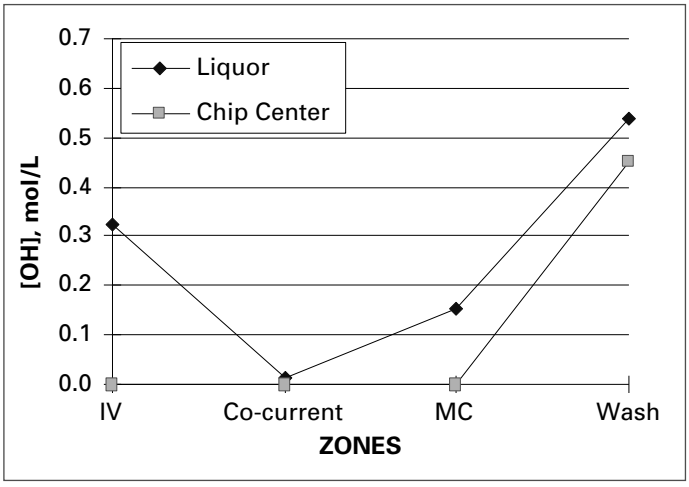
Cold blow alkalinity

In LoSolids™ pulping, wash filtrate liquor (referred to as cold blow) is added to the digester at various points to achieve a low dissolved solids liquor. Lowering the dissolved solids improves pulping performance [6]. The cold blow residual EA is low compared to the other digester circulation loops, and its effects on pulping are assumed negligible. However, the EA concentration fluctuates from the washers to the digester, and it may affect pulping. In the commercial system studied for this work it appeared that the cold blow residual EA could vary from 1-8 g Na_2O/L.

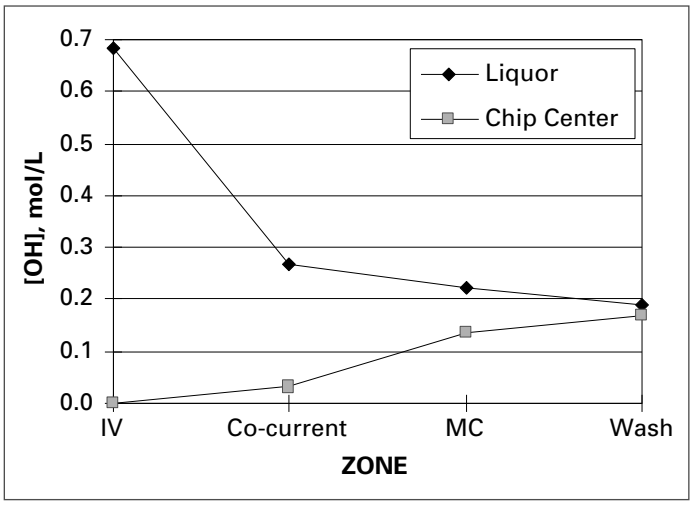
We ran the model to assess whether these variations in cold blow EA concentration could affect the final kappa. Six cases were simulated where the cold blow concentration varied from 0 to 10 g Na_2O/L. The pulping conditions and chip thickness distribution was the same as that used to verify the model for modified cross flow LoSolids™ cooking.

Figure 7 shows that changes in the cold blow concentration have a definite effect on the final kappa. Over the range of cold blow alkalinities observed by the mill (1-8 g Na_2O/L) the kappa could vary about 5 or 6 points.

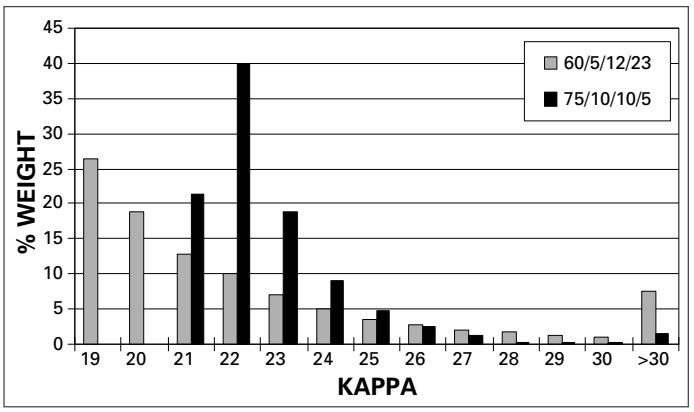
Figure 8 exhibits the extent to which cold blow EA concentration variations affect the residual alkali concentrations in a given zone.



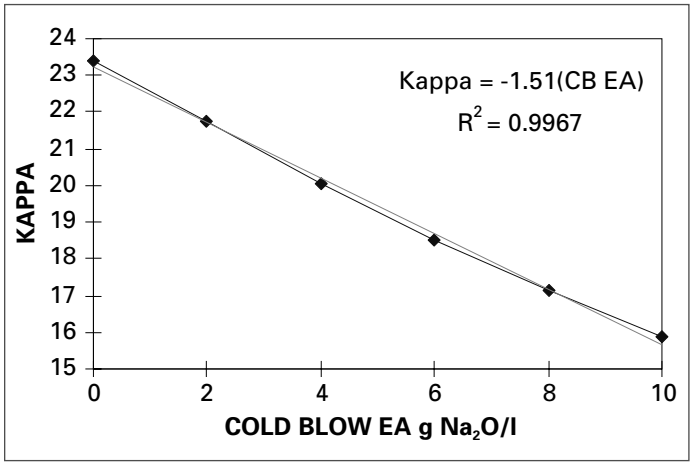
4. Alkali profile for 60/5/12/23 liquor split.



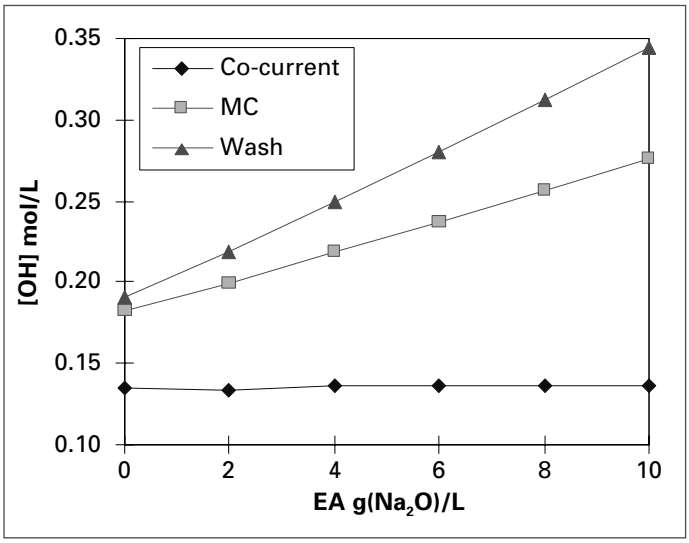
5. Alkali profile for 75/10/10/5 liquor split.



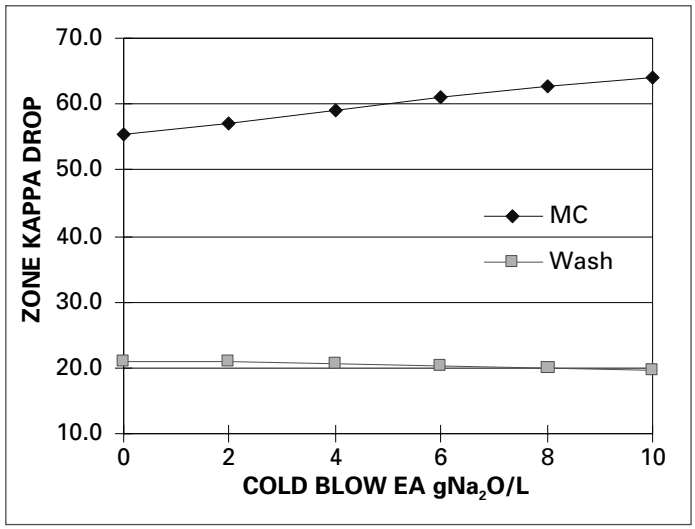
6. Kappa profile for two liquor splits (See Table VII).



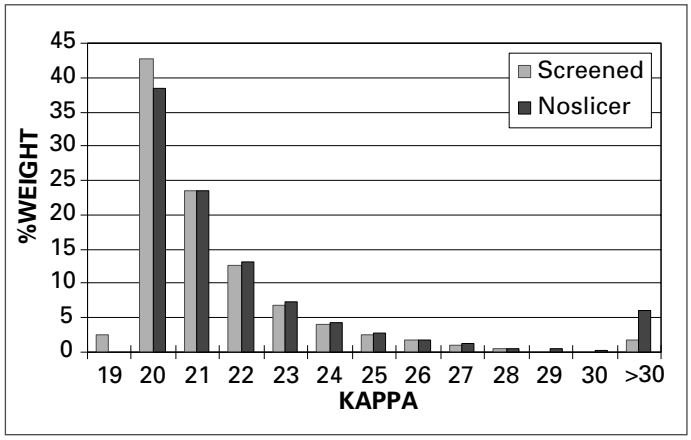
7. Cold blow effect on final kappa.



8. Influence of cold blow filtrate EA concentration on zone residual alkali concentrations.



9. Cold blow EA influence on MC and wash zone kappa drop.



10. Kappa uniformities for screened and untreated overthick chips.

As expected, the cold blow residual EA has the most effect on the wash zone EA and a milder effect on the MC zone alkalinity.

We also examined the response of the delignification in each zone to the change in cold blow EA with the model. **Figure 9** shows the extent of delignification in the MC and wash zones. Somewhat surprisingly, the wash zone delignification was virtually unaffected by the cold blow residual EA and the change in over all kappa shown in Figure 7 is mainly due to pulping changes in the MC zone. The response of a zone to changes in alkalinity depends on the overall delignification rate in that zone. Changes in alkali concentration will be felt more in zones with rapid delignification. Pulping is much faster in the MC zone than in the wash zone because delignification is in the bulk phase.

Thickness screening

We used the digester model to examine some issues associated with the chip supply. The pulping model can handle up to four different chip sizes in the chip size distribution. Mills can use it to examine the effect of chip thickness screening on pulping performance.

Approximately 20% of the raw wood supply to the mill is overthick chips (>8mm). The overthick chips are reduced in a slicer to accepts (3-7mm) and up to 15% of the sliced overthick wood is reduced to pins (<3mm). The model was used to examine the effect on pulping of not slicing the oversized fraction. Information obtained from the mill, revealed that turning off the slicer resulted in the following chip thickness distribution, as shown in **Table VIII**.

The pulping conditions used for these simulations were the same as that used to verify the model for modified cross flow LoSolids™ cooking.

The simulations predict that the end kappas for the sliced and unsliced chips were 21.2 and 22.3 respectively. All other variables including temperatures, flows, digester kappa profiles, and zone residual alkali concentrations were virtually the same. **Figure 10** shows that the kappa uniformity for the two cases is similar. However, there are significantly more high kappa fibers in the unsliced case. Some of this will be screened as undercooked thick chip centers and we would anticipate that the screen rejects would increase as a result of this chip size change. The capacity of the pulp screens would be an

important factor in the mills handling of unsliced chips. However, much of the pulp in the higher kappa range will go on to the bleach plant. These fibers will consume an excess of bleaching chemical commensurate with their high kappa number. Generally, however, both kappa uniformities are very good. This indicates that the mill can still realize a reasonable kappa uniformity without reducing the overthick chips and shows that Kamyr digesters running in the LoSolids™ mode can handle thick chips without a significant impact on the pulping uniformity. In any event, the conditions of the digester could be modified, changing the white liquor split for example, when pulping unsliced chips to produce a similar kappa profile to that obtained with the sliced chips.

CONCLUSIONS

We developed a pulping model to look at the operation of a continuous digester operated in EMCC™ and LoSolids™ cook modes. The model tested well. No tuning of the default softwood kinetics was necessary to predict accurately the kappa of the final pulp.

The model was used to investigate some operational issues, and the following conclusions summarize the findings from the studies. The white liquor feed split can be modified to achieve an optimal kappa profile through the digester and improve pulping uniformity. More white liquor to the front of the digester results in less pulping being required in the wash zone and in better pulping uniformity. The white liquor feed split can be optimized to allow the digester to pulp thicker chips without adversely affecting pulp uniformity. Pulp uniformity and the benefits of balancing delignification through the various digester zones should be considerations when deciding what white liquor split to use.

Cold blow residual EA can influence the final pulp kappa. Mills need to control this variable to have a stable digester kappa number. Overthick chips have a moderate affect on pulp uniformity for the digester configuration studied in this project. Turning off the slicer did not appear to significantly affect pulp uniformity for this mill.

In general, the model worked well when applied to a continuous digester. The challenge of the modeling was to get an accurate picture of the actual operating conditions. The model provided considerable insight into the digester operation that would not be brought to light without its use. **TJ**

THICK (mm)	LENGTH (mm)	%WT. DIST.
3	15	12.4
4.5	20	67.6
7.8	25	8.2
11.1	25	11.8

VIII. Chip size distribution for unsliced chips.

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INSIGHTS FROM THE AUTHORS

Q. *Why did you choose this topic to research?*

A. The mill we did this research for was interested in using our modeling technology to improve their digester operations

Q. *How does this compliment or support your previous research?*

A. We have done considerable research on pulping and digester modeling. This project was nice because it dealt exclusively with a commercial reactor.

Q. *What was the most difficult aspect of this research and how did you address that?*

A. The hardest part was getting accurate data on the operation of the digester. The problem was addressed by collecting lots of data then carefully screening that data to remove outliers.

Q. *What did you personally discover from this research? What was most interesting or surprising about your findings?*

A. The project showed that commercial digester could be modeled with good accuracy.

Q. *What's the next step?*

A. We continue to do research on modeling of digester operations.

— Richard R. Gustafson



Walkush



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