Comparative evaluation of conical and double disk refiners: Effects of operating mode, refining intensity, and device geometry on energy consumption and paper properties

HANNAH MILNE, HAIXUAN ZOU, COLLEEN WALKER, AND FRITZ PAULSEN

ABSTRACT: This study investigates the effects of refiner operating mode and refining intensity adjusted via pulp flow rate, applied power, and refiner speed on the refining characteristics of high-yield southern softwood. We compared Valmet's OptiFiner PRO (conical) and DD6700 (double disk) refiners under matched specific edge load (SEL) conditions. Batch and one-pass modes were evaluated for their impact on energy efficiency and physical paper properties.

The results showed that while SEL provides a useful baseline, it does not fully account for differences in refiner geometry, particularly angular parameters. With the chosen plate sets, C-factor analysis revealed that the OptiFiner PRO delivers a lower number of fiber impacts at a higher intensity per impact compared to DD6700 at similar SEL, influencing fiber length, short-span compression test (STFI) index, and tear strength development. These findings offer actionable insights for mills seeking to optimize refining efficiency and cost. In summary, conical refiners may provide advantages in compression strength at mid-range energies, while double disk refiners maintain higher tear strength at elevated energies due to better fiber length preservation.

Application: Readers can use the information in this study to gain a fundamental understanding of the similarities and differences between conical and double disk refining technologies, particularly in terms of energy efficiency and strength development for high yield southern softwood used in unbleached linerboard and kraft bag production. This research provides valuable insights for mills looking to update their machinery and improve their refining processes to reduce carbon footprint and enhance fiber strength.

Various refining technologies for low consistency treatment of paper machine stock have been around for some time, from the simple Jordan refiner tubs to the most recent advances in lower angle flow through plate conical technology. Key developments implemented over the years, from floating shafts to splined hub technology, improved the following: hydraulic throughput (for energy improvements); plate designs (for improved safety); fiber properties; maintenance requirements; and plate life. Likewise, the introduction of gap control and anti-clash technology, etc., have made significant strides; however, the overarching goals of the refining process have remained unchanged. The primary objectives of refining have remained imparting improved sheet properties (smoothness, porosity, optics, and/or strength) at the lowest energy possible while resulting in manageable papermaking impacts (i.e., drainage, fines impact, drying, etc.).

As paper mills look to upgrade or build from the ground up, this study compares the performance of two modern refiner designs. Whether mill goals are based on energy savings or fiber strength development or both, the overall purpose is to provide information with an unbiased evaluation of state-of-the-art DD 6700 series twin gap double disk vs. Optifiner Pro conical flow through refining technologies for unbleached containerboard softwood. Furnish types do play a critical role, from recycled to semichemical to kraft-based virgin content, in refining strategies but were not the focus of this study. All refining was conducted on high kappa softwood kraft from a southeastern U.S. mill with the intention for incorporation in kraft linerboard and bag production. The experimental design utilizes specific edge load (SEL) theory, one of the most popular and easier refining theories to understand, while better interpretation of the results was gained utilizing C-factor theory accounting for the refiner geometries, the number of impacts, and the intensity of fiber impacts.

MATERIAL AND METHODS

Applied theories

The initial approach was to design the refiner experimental comparison utilizing one of the most popular and utilized refining theories utilized today, namely SEL. Brecht [1] summarized this popular two-variable approach, demonstrating that a change in property could be directly correlated to a two-parameter model, Eq. 1, where E_{net} represents a quantity or specific net energy applied, represented by Eq. 2, and S_e represents the intensity of treatment or SEL in Eq. 3. Properties of Eq. 1 can include things like freeness and strength results. This was later followed by several additional theories [2-11] by well-known authors in the field to add additional considerations for specific area, refiner geometries, and number of fiber impacts.

$$\Delta Property = f(E_{net}, S_e) \quad (1)$$

where:
E_{net} = net specific energy, horsepower days (hpd)/ton or kWh/ton
S_e = SEL, watt-second per meter (W-sec/m)

Then, E_{net} and S_e can be characterized by:

$$E_{net} = \frac{(P-P_0)}{Q\,\rho\,c}\text{, hpd/ton or kwh/ton} \quad (2)$$

$$S_e = \frac{(P-P_0)}{L_r\,\Omega} \quad \text{W-sec/m} \quad (3)$$

where:
P = total refining power, hp
P_0 = no-load power, hp
Q = flow rate, gpm
ϱ = stock density, lb/gal
c = stock consistency, %
L_r = bar crossings per revolution, km/rev
Ω = rotational speed, rpm

with appropriate unit conversions applied below,

$$E_{net}\left(\frac{hp\ days}{ton}\right) = \frac{(P-P_0),\ horsepower}{Q\,\rho\,c,\ US\ tons/day}$$

where:

$$Q\,\rho\,c\left(\frac{US\ tons}{day}\right) = \left(\frac{gal}{min}\right)\left(\frac{8.33\ lbs}{gal}\right)\left(\frac{lbs\ stock}{lbs}\right)\left(\frac{60\ min}{hr}\right)\left(\frac{24\ hr}{day}\right)\left(\frac{ton}{2000 lbs}\right)$$

$$S_e = \frac{(P-P_0),horsepower\ \left(\frac{0.746\ kw}{hp}\right)}{L_r\left(\frac{km}{rev}\right)\ \Omega\ \left(\frac{rev}{min}\right)\left(\frac{1\ min}{60\ sec}\right)} \quad \text{W-s/m}$$

Kerekes [3] describes the calculations for C-factor and number impacts. The starting point follows similarly to the two-parameter theories mentioned previously. Kerekes stated that the refining energy is directly related to the number of impacts, N, and the intensity of those impacts, I, as represented by Eq. 4:

$$E = N \times I \quad (4)$$

where:
E = energy per mass
N = number of impacts per unit mass
I = energy per impact

Eq. (4) can be further broken down to produce the C-factor, with:

$$E = (C/F) \times (P/C) \quad (5)$$
$$N = C/F \quad (6)$$
$$I = P/C \quad (7)$$

where:
P = Net power applied to pulp through a refiner, (total load – no load)
F = Fiber mass flow through the refiner
C = C-factor, which is the measure of refiner capacity to impart impacts on the fibers

where F can be broken down into practical and familiar refining terms by Eq. 8.

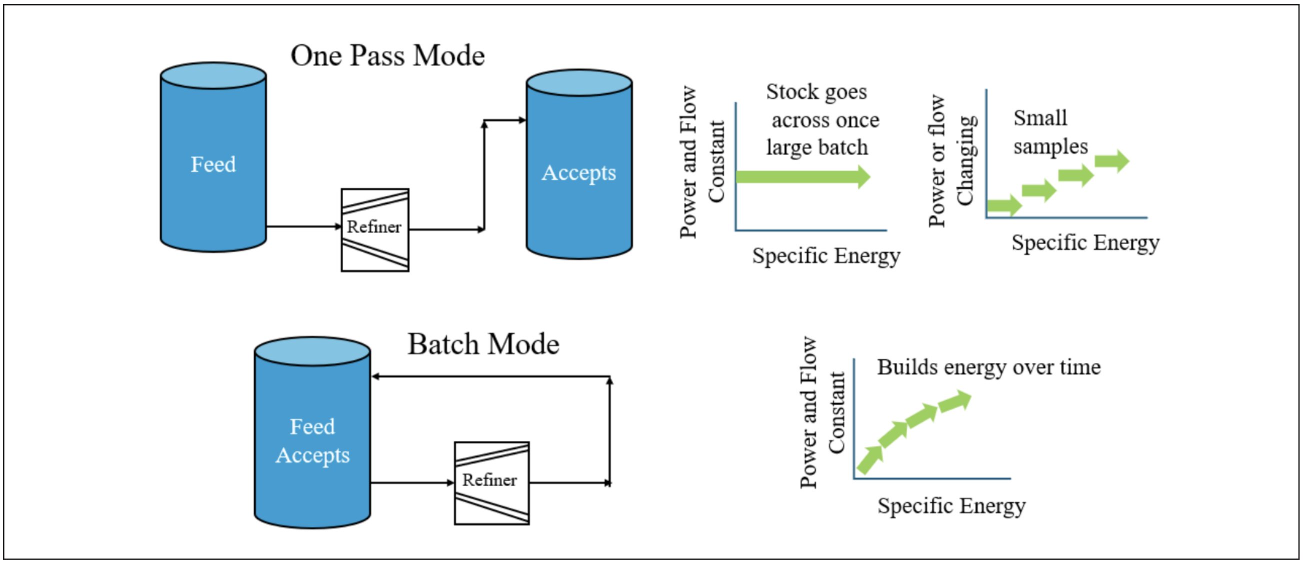
$$F = Q\ \ \rho\, c \quad (8)$$

where Q, ρ, and c are described above in the SEL theory as the mass flow rate calculation in the denominator of Eq. 2.

The C-factor measures the capacity of a refiner to impose impacts on pulp fibers with the thought that equal C-factors mean that refiners will behave similarly. It was derived to provide for a simple quantitative characterization of pulp refiners. As refiner geometries and shapes and sizes of refiners continue to emerge, the theories that account for the various geometries will become of more importance to interpreting the empirical results. These derived equations are provided by Kerekes [3] and will not be part of this scope but will be revisited in the interpretation of the results across refiner types. Kerekes provided mathematical relationships based on refiner geometry, whether it be a disc configuration or a conical design, and these will be used in the interpretation of the results.

Batch vs. one pass refining experiments

Understanding the impact of refining mode — batch (100% recirculation) vs. one pass (tank-to-tank) — is critical for both laboratory relevance and mill-scale application. **Figure 1** graphically shows some of the more common pilot or laboratory refiner methods to simulate mill refining. Kerekes [12] provided a theoretical foundation for re-



1. Typical operating and sampling configurations for pilot and laboratory refining.

circulation effects, but empirical data on fiber property development under these modes remains limited.

In this study, we systematically compared true batch mode (continuous recirculation in a well-mixed tank, simulating a continuous stirred tank reactor — CSTR) with one pass mode (tank-to-tank or series refining). Both approaches were designed to maintain comparable refining intensity and specific energy input, ensuring that observed differences could be attributed to the mode itself rather than confounding variables.

Batch mode offers significant logistical advantages in pilot and laboratory settings, especially when pulp quantity, experiment duration, and budget are constrained. It allows for efficient energy accumulation and uniform treatment of the entire furnish, while one pass mode more closely mimics commercial mill operations investigations.

Our experiments revealed that, under matched conditions, batch and one pass modes produced statistically similar fiber property outcomes across key metrics (e.g., strength, freeness), even as energy input increased. This suggests that batch mode is a valid and efficient surrogate for one pass mode in pilot-scale studies, without compromising data quality or relevance to mill operations. The main practical difference was operational efficiency: batch mode required significantly less time, about one-seventh that of one pass mode, to achieve comparable results.

These findings support the use of batch mode for large-scale pilot work, enabling more rapid and resource-efficient experimentation while maintaining confidence in the predictive value of the results for industrial refining scenarios.

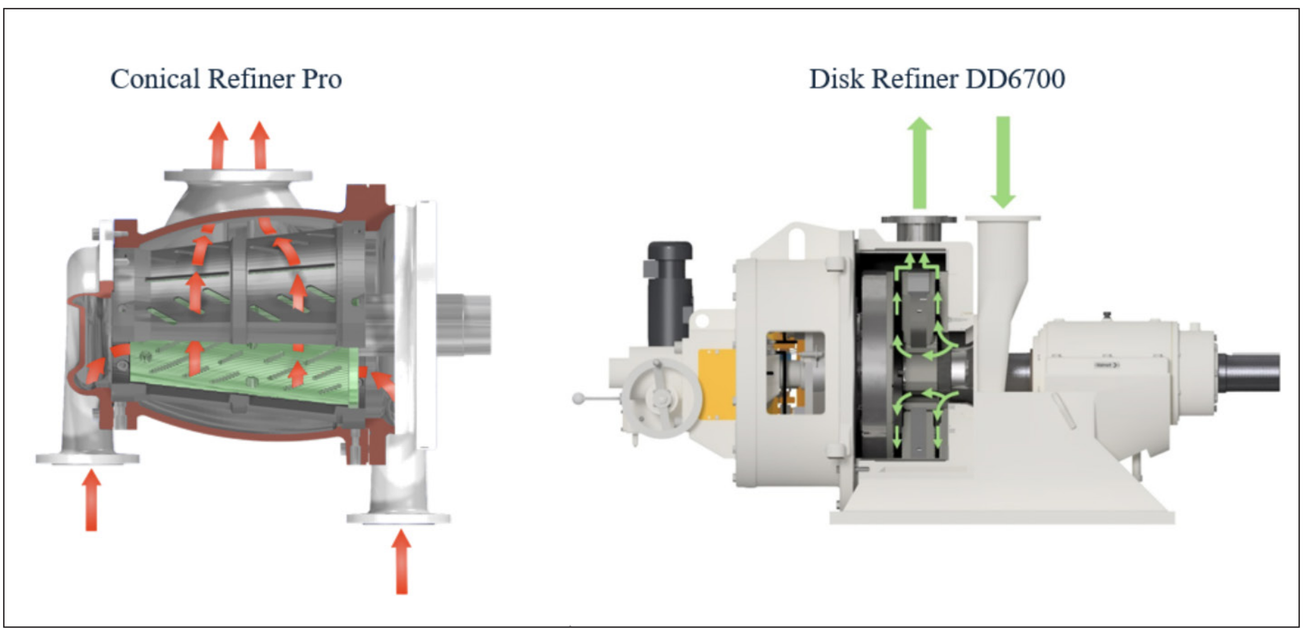
EXPERIMENTAL

One hundred percent virgin high kappa softwood market roll pulp was shipped to the Process Development Center at the University of Maine in Orono, ME, USA. Material was sheeted and fully repulped in the hydrapulper for 30 min under a nominal pH of about 8.0 and temperature of about 25°C at 6% consistency. This produced no visible broke flakes. After repulping, the furnish was transferred to the refiner feed tank and diluted to a refining consistency target of about 4%. Batch sizes of approximately 1800 gal to 3200 gal for running the refiner were typical. A sampling from each of the available pulp rolls was taken to measure the initial pulp properties. These included freeness, MorFi values (fiber length, fines, etc.), water retention values (WRVs), and TAPPI handsheets made for tensile, tear, burst, and short-span compression test (STFI) index calculations. These initial samples represented the zero point on our refining specific energy scale. These tests were repeated at various predetermined SEL setpoints at roughly every 3 hp-days/ton to satisfy Eq. 1 for property developments, keeping both specific energy and intensity similar for each run.

A 20-in. diameter double disk Valmet 6700 series refiner was utilized to represent the double disk condition. A Valmet Optifiner PRO1 with plate flow through design was utilized to represent the conical refiner. These PRO designs represent a much lower cone angle than traditional conical refiners, and the main difference is that flow is introduced to the rotation of the plates through the rotor plates vs. from the entrance of the cone from a traditional conical refiner. Both refiners used reside at the University of Maine Process Development Center and are pictured in **Fig. 2**. Flow through configurations of both units have been included in **Fig. 3**, courtesy of Valmet.

Plate patterns used for both refiners are commercially available, and relevant data are shown in **Table I**. The same plates respective to each refiner were utilized throughout the entire trial. The plate design and rotational speeds were chosen to produce similar peripheral velocities, while main-

2. Valmet Optifiner PRO1 conical refiner model (left) and DD6700 double disk refiner model (right). Photo courtesy University of Maine Process Development Center.



3. Fiber flow paths of the two refiners. Graphics courtesy of Valmet.

Refiner	Plate ID	Edge Length, km/rev	Bar Angle	Bar Width, mm	Groove Width, mm	Bar Height, mm
Optifiner PRO1	PRO1RC02G/SC02G	5.3	30° rotor 10° stator	2.5	3.5	7.0
DD6700 20 in.	20BJK103/104	4.85	10°	Outer 2.67 Inner 3.05	Outer 3.68 Inner 4.14	Outer 7.14 Inner 7.82

I. Plate pattern details for the comparison trials.

taining the two parameters of SEL theory constant for comparison. Refiner flow, power inputs, and rotational speeds were adjusted to maintain these parameters and are indicated for each trial. Three slightly different parameter runs were made for each specific energy and intensity setpoint to empirically test the two-parameter model against common properties. Slight changes in the rotational speeds were compensated for with flow and power adjustments to reach the same parameters to satisfy Eq. 1. For typical unbleached southern softwood kraft pulps, refiner manufacturers recommend an intensity range of 2.5 to 4.5 W-sec/m for low consistency refining operations. This work set the intensity at about 2.9 W-sec/m for all trials.

Resulting refining stock conditions were evaluated for Canadian standard freeness (CSF) using TAPPI Standard Test Method T 227 “Freeness of pulp (Canadian standard method),” and starting furnish from the delivered softwood roll pulp was measured across five separate repulper batches with an average starting fiber freeness of about 734 mL and a standard deviation of 14 mL. Fiber morphological determinations were made by a MorFi camera instrument system (Techpap; Grenoble, France) on the principles of ISO 16065-2 “Pulps — Determination of fibre length by automated optical analysis — Part 2: Unpolarized light method,” and these were measured for each refining sample point. A softwood starting fiber length of 2.3 mm with a fiber coarseness of 0.331 mg/m was used for all calculations. Pulp kappa number was measured using TAPPI T 236 “Kappa number of pulp” and was taken from an average of six measurements over the complete sampling of the received roll pulp, with about a 98-kappa number and a 3-kappa unit standard deviation. Handsheets for strength properties were made utilizing TAPPI T 220 “Physical testing of pulp handsheets,” although modified utilizing 2-g handsheet targets to better represent a typical unbleached linerboard basis weight. STFI, tensile, burst, and tear were measured using TAPPI T 826 “Short span compressive strength of containerboard,” T 494 “Tensile properties of paper and paperboard (using constant rate of elongation apparatus),” T 403 “Bursting strength of paper,” and T 414 “Internal tearing resistance of paper (Elmendorf-type method),” respectively, and normalized to their indices by handsheet weight with appropriate replicates made for each refiner sample condition. The WRVs were measured according to TAPPI UM 256 “Water retention value (WRV).” Error bars in all measurements were calculated by standard error

Refining Parameter	Units	Batch or One Pass Mode
Refiner speed	rpm	700
Plate design	km/rev	4.85
Plate diameter	in.	20
No load	hp	55
Total applied power	hp	272
% Consistency	%	4.0
Refiner flow	gpm	302
Peripheral speed	m/s	18.6
Net specific energy per pass	hp-days/ton	3.00
SEL intensity	W-sec/m	2.9

II. Experimental conditions of the DD6700 refiner to compare single pass vs. 100% recirculation (SEL: specific edge load).

calculations that are equal to the standard deviation of the data set divided by the square root of the number of samples.

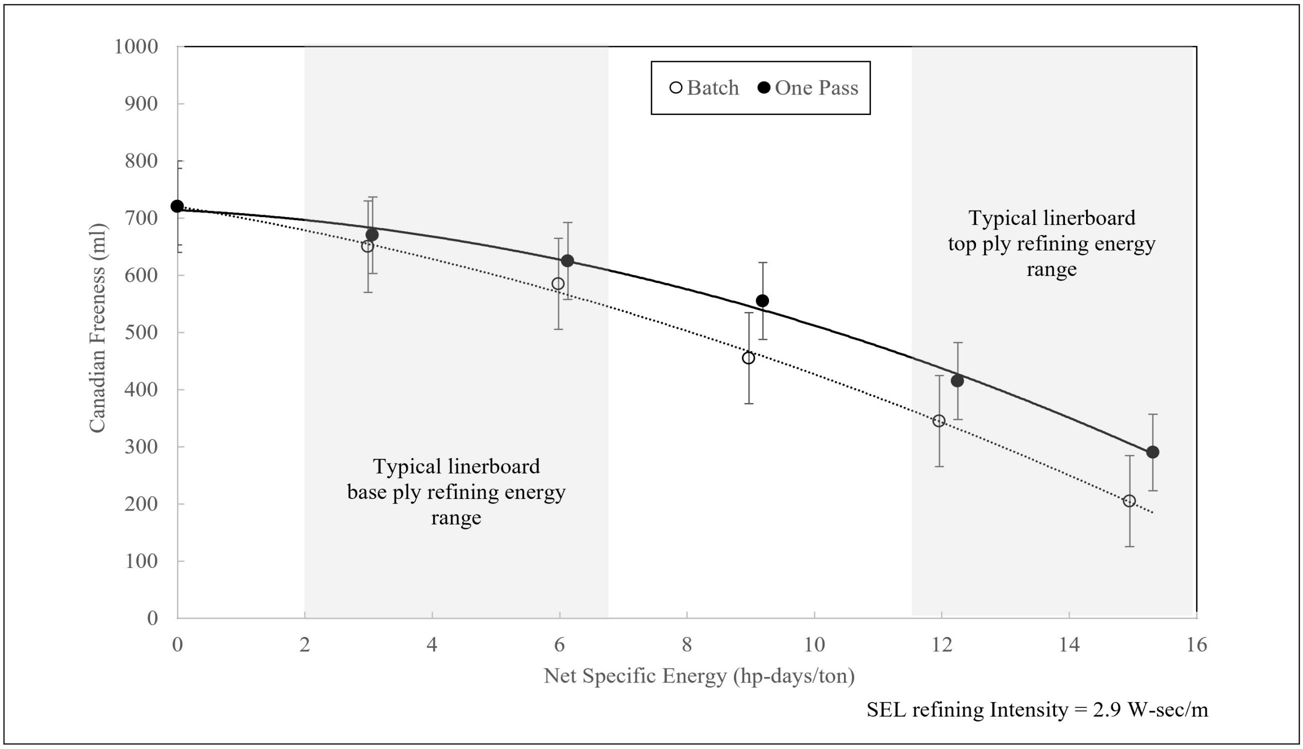
Batch mode vs. single pass comparisons were only run for the DD6700 refiner; the conical refiner was not included in this phase. Two runs were compared at the same energy and intensity inputs per Eqs. 1–3 from the SEL theory. The difference in the mode of refining was shown earlier in Fig. 1. Staircase power sampling was not utilized for these trials; only 100% recirculation vs. one pass multiple times were compared. To simulate multiple passes in the one pass mode, all furnish was run through the refiner with mill level settings. The entire batch was run through the refiner tank-to-tank, shutting down just as the feed tank reached the minimum level of agitation for consistency control. The remaining feed side pulp was sewered, and the pulp from the refining accepts tank was pumped back to the feed tank to start again for the second pass. This was repeated five, with total energy of about 3 hp-days/ton applied each pass through the refiner. This best represents actual "In Series" commercial refining, as stock can pass through multiple refiners on its way to the paper machine headbox. For the batch mode of Fig. 1, only one tank was utilized and refined furnish was continuously returned to the feed tank, representing a mill condition with 100% recirculation. Furnish was very well mixed in the tank, and specific energy was accumulated on time. The samples were taken at an interval of 3 hp-days/ton applied to the entire tank at each sampling. The same refiner settings that were used in the one pass mode were replicated in the batch mode.

Table II lists the DD6700 set points for both runs. Trials targeted a net specific energy of about 3.0 hp-days/ton per refiner pass while maintaining a constant intensity of about 2.9 W-sec/m. This intensity range was chosen to be within the typical range for unbleached high kappa softwood for linerboard production. Rotational rates and net power were adjusted according to the intensity calculation of Eq. 3.

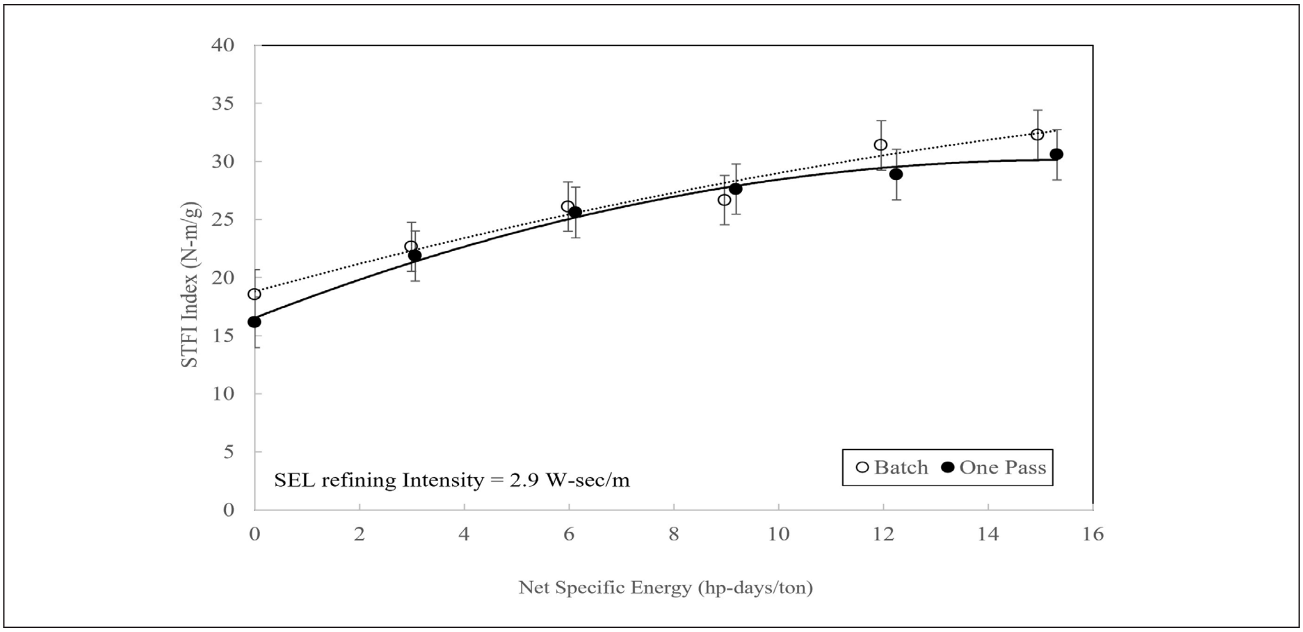
RESULTS AND DISCUSSION

Batch mode vs. tank-to-tank mode using the DD6700 refiner

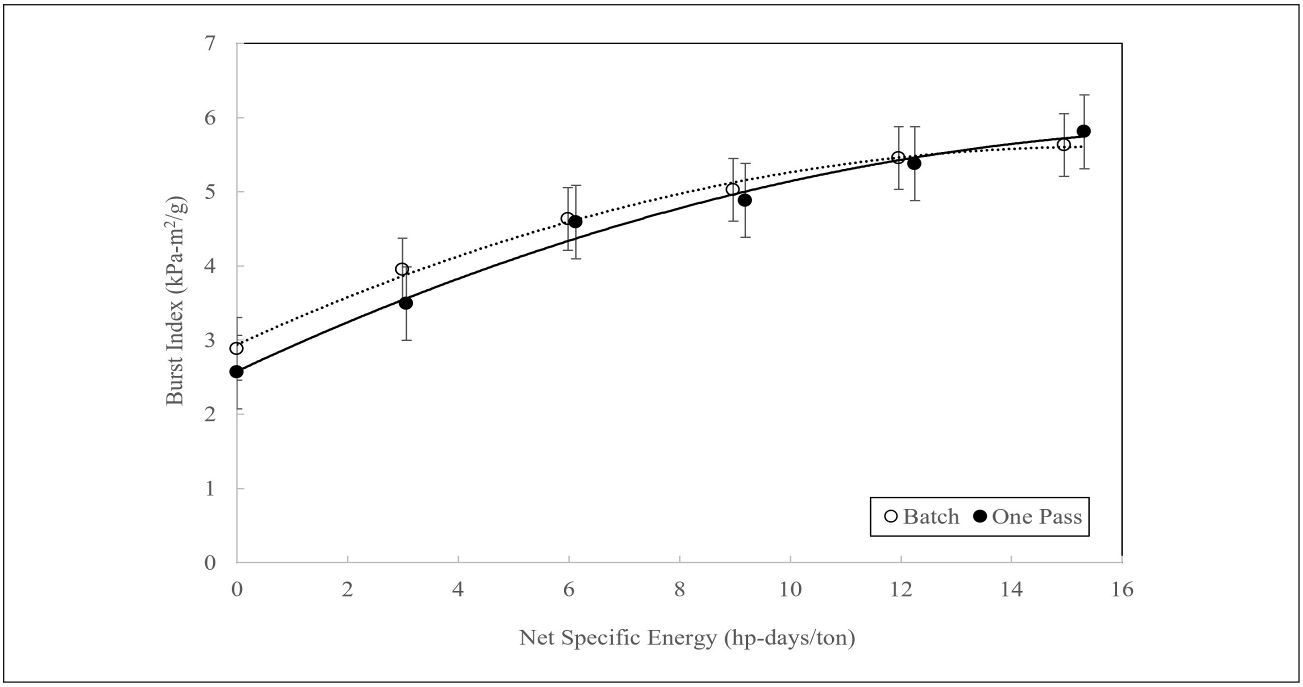
Samples were collected at the outlet side of the refiner at similar calculated net energy and intensity inputs, and the physical properties were compared. The results can be seen in **Figs. 4–7**, representing the property changes vs. net specific energy and intensity of Eq. 1 for CSF, STFI index, burst index, and tear index vs. tensile index, respectively. In Fig. 4, a slow divergence of the CSF curve was seen, which approached the point of statistical significance but remained similar in the data sets as the batch vs. one pass data passes through linerboard base ply and top ply specific energy ranges. For the 2 to 6 hp-days/ton specific energy range for typical linerboard base ply refining energies, a p-value of 0.158 was seen, indicating no statistical difference in this region. As the energy approached 12 to 15 hp-days/ton, p-values shifted slightly, with a p-value of 0.123



4. Canadian Standard Freeness development vs. applied specific energy for batch vs. one pass refining modes (SEL: specific edge load).



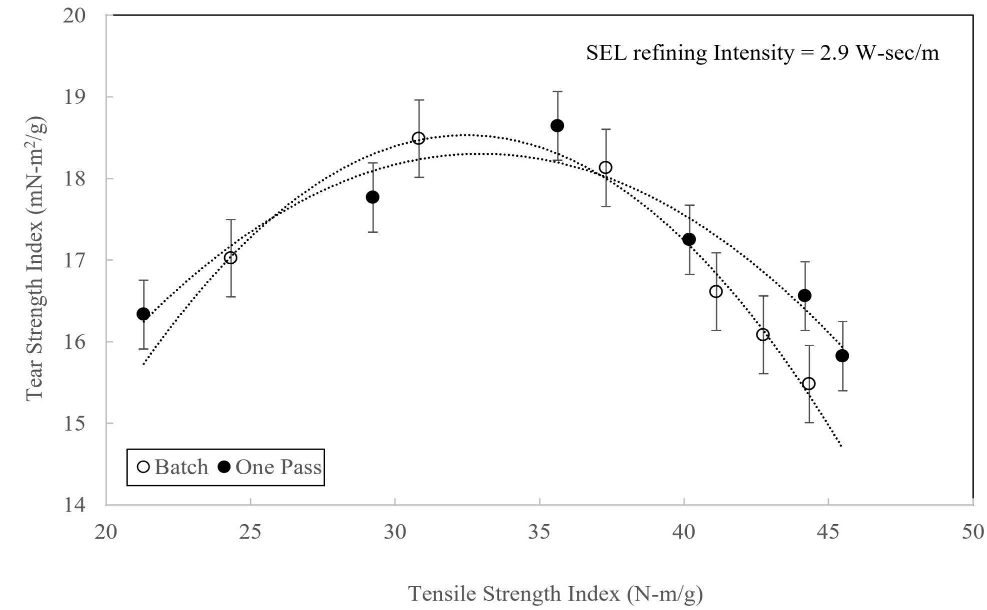
5. Short span compression index vs. specific energy applied for batch vs. one pass refining modes.



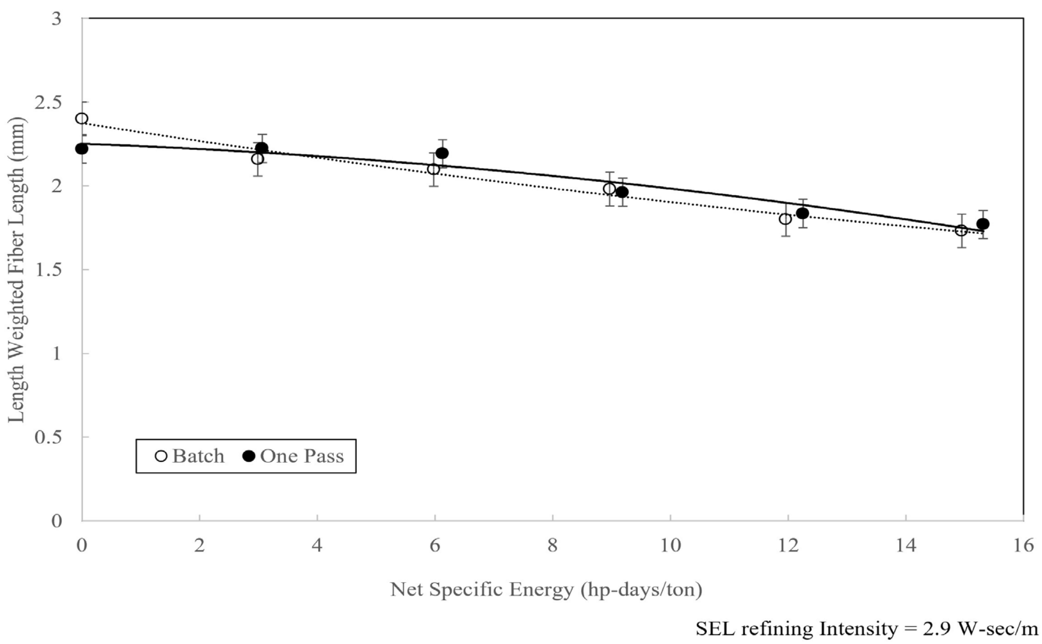
6. Burst index vs. specific energy applied for batch vs. one pass refining modes.

also indicating no significance statistical difference. These *p*-values do suggest additional data is needed to gain further confidence. This may be due to the increased opportunity for fiber in a 100% recirculation mode to see a refiner bar more than once.

After analyzing the refined pulp for strength characteristics, it was seen that the resulting physical properties were statistically similar to each other regardless of mode, even as energy was increased. Any freeness difference was not enough to drive the physical strength differences for STFI and burst. This can be seen with overlapping compression strength and burst index values across the specific energy inputs, regardless of mode. However, tear index vs. tensile index trends were very similar as well, demonstrating the familiar peak in tear strength as tensile continues to build. A small divergence of the tear tensile plot at the edge of the error bars was noted at very high specific energies, approaching 14 hp-day/ton levels. This may have some implications in top ply refining conditions but certainly not for traditional base ply linerboard refining. Examination of the



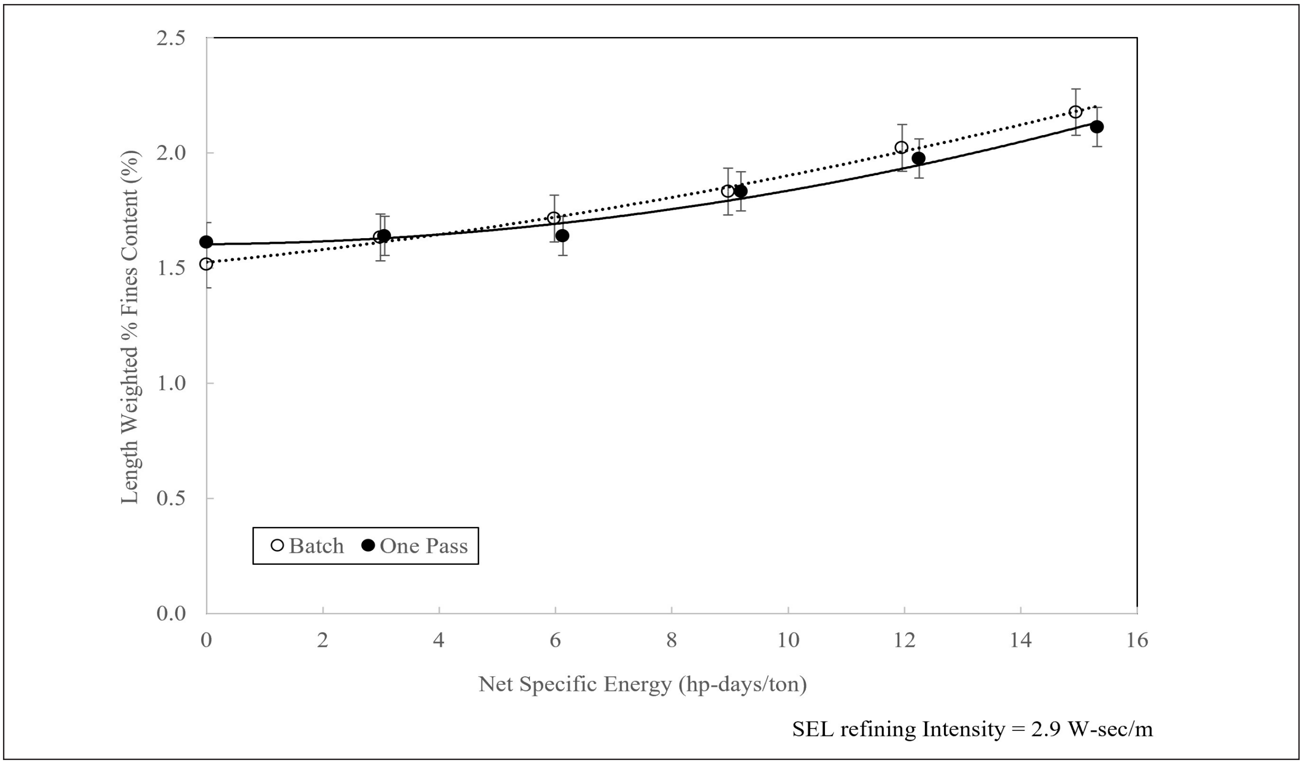
7. Tear index vs. tensile index for batch vs. one pass refining modes.



8. Length weighted fiber length for batch vs. one pass refining modes.

length weighted fiber length and length weighted fines over increasing energies in **Fig. 8** and **Fig. 9** did not produce any substantial differences in fiber shortening between batch and one pass modes to explain the increasing difference in CSF as energy increased.

In the pilot and laboratory setting, practical refiner time and efficiency are needed; optimal use of pilot trial time and the budget all must be considered when setting up pilot experiments. The largest difference encountered between batch and one pass modes for the large pulp quantities needed was that setting up the one pass refining mode took seven times the amount of time that the batch mode refining took to achieve similar strength interpretation outcomes. Generally, the batch mode took anywhere from 30 min to 40 min to run the spe-



9. Length weighted percent fines development for batch vs. one pass refining modes.

cific energy curves, while the one pass mode took 3.5 h, with a lot of stock pumping and transference to get it done. Based on the statistical analysis and results mentioned previously, moving forward from the experimental procedure, it was decided that batch mode would be utilized for the comparison of the DD6700 to the conical OptiPRO1 refiner in the best interests of time and scope.

Optifiner PRO vs. DD6700 refiners

Literature has compared double disk (DD) and conical refiners in the past [13,14]. Based on this knowledge and using Eqs. 1–3, three sets of conditions were created for both the DD refining and the conical refining. A calculator utilizing these equations was used to find SEL conditions to set the inputs for the refiners. A 20-in. Valmet 6700 series refiner was utilized to represent the DD condition. A Valmet Optifiner PRO1 with plate flow through design was utilized to represent the conical refiner. Since SEL was being used to define refining conditions, refining calculations were made to adjust motor revolutions per minute, power input, and refiner flow to maintain constant intensity while running to batch mode (100% recirculation) while building specific energy over time with tank recirculation. In total, six total trials were compared throughout the entire study, the first three set conditions being shown in **Table III** for the double disk (DD6700), and the remaining three shown in **Table IV** for the conical (Optifiner PRO1) conditions. Note that although slightly changing the rotational speed for each run and then adjusting flow and power, the six different trials were all calculated to have a similar net specific energy applied per refiner pass, 3.0 hp-days/ton, and a similar SEL intensity, approximately 2.9 W-sec/m. The DD no load power was determined experimentally with stock on refiner at study flow condition and consistency with the plates completely gapped out. Changes were purposefully made to empirically test the two-parameter model by adjusting the inputs of Eq. 2 and Eq. 3 to get to the same calculated result for E_{net} and S_e per Eq. 1 through a slightly different path.

The double disk refiner run conditions are shown by runs A, J, and H, represented in Table III, while the conical refiner runs were G, F, and C, represented in Table IV. The runs were named alphabetically, and the missing letters are trials where there were miscellaneous errors, such as not hitting the target intensities, inconsistent refiner activity, aborted runs, etc. This data is not included.

The rotational speed was set to 700, 756, and 800 rpm for runs A, J, and H, respectively for the DD6700. The total power (including the no load) calculated to correspond with these rotational speeds were 272, 302, and 306 hp, respectively. Net power can be achieved by subtracting no load power from total power as indicated in Eqs. 2, 3, 5 and 7. As for the conical runs, the rotational speed was set to 756, 840, and 900 rpm for runs G, F, and C. The total power (including the no load) for these rotational speeds was 289, 323, and 350 hp, respectively. Conical no loads were determined empirically for each run by measuring the horsepower with the desired flow rate at the desired refining

Batch Recirculation Mode	Units	Run A	Run J	Run H
Refiner speed	rpm	700	756	800
Plate design	km/rev	4.85	4.85	4.85
Plate diameter	in.	20	20	20
No load	hp	55	64	55
Total applied power	hp	272	302	306
% Consistency	%	4.0	4.0	4.0
Refiner flow	gpm	302	330	349
Peripheral speed	m/s	18.6	20.1	21.3
Net specific energy per pass	hp-days/ton	3.00	3.01	3.00
SEL intensity	W-sec/m	2.86	2.91	2.90

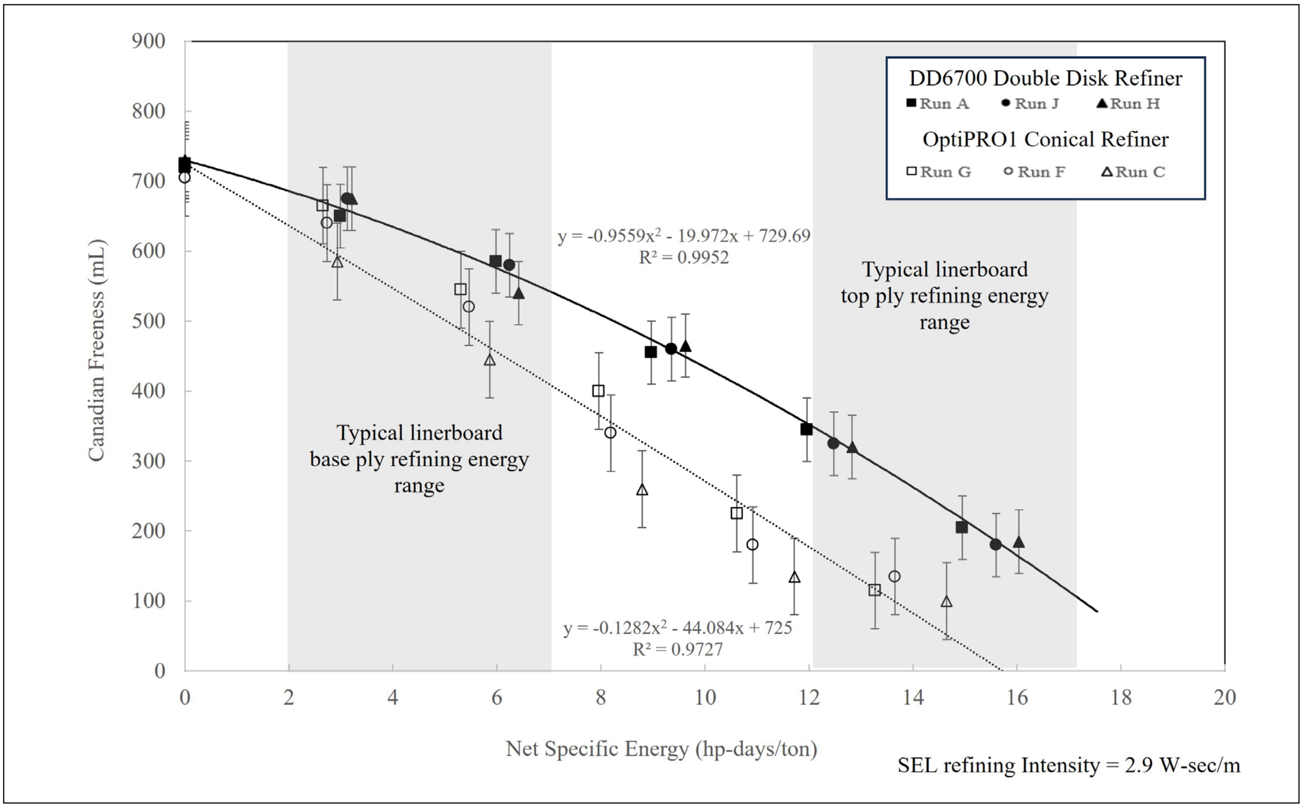
III. The DD6700 refining target settings.

Batch Recirculation Mode	Units	Run G	Run F	Run C
Refiner speed	rpm	756	840	900
Plate design	km/rev	5.30	5.30	5.30
Plate diameter	in.	13.4	13.4	13.4
No load	hp	28	35	39
Total applied power	hp	289	323	350
% Consistency	%	4.0	4.0	4.0
Refiner flow	gpm	361	400	420
Peripheral speed	m/sec	13.5	15	16
Net specific energy per pass	hp-days/ton	3.01	3.00	3.09
SEL intensity	W-sec/m	2.92	2.90	2.92

IV. The Optifiner PRO1 refining target settings.

stock consistency with the refiner gap fully open. Once the refiner was gapped in and additional net power applied to hit the total power targets, these conditions all calculated an approximate SEL of 2.9 W-sec/m and were held constant for all runs. Peripheral velocity was calculated to be in a similar range but not held constant, and it tended to be higher for the conical refiner to achieve similar specific energy and intensity settings. The peripheral velocity for the conical refiner was calculated at the larger diameter of the rotor at 13.4 in., while the diameter of the DD6700 plates used was 20 in.

After the six runs were completed, the physical properties of the pulp were measured at each additional 3.0 hp-days/ton sampling point up to a total applied net specific energy of 12 to 15 hp-days/ton. For each refiner geometry, the three runs arrived at a similar specific energy range using a similar intensity target of 2.9 W-sec/m from the refining parameters established in Table III and IV. **Figure 10** shows the relationship between the freeness of the pulp and the net specific energy used during the refining process of both refiner types for all runs. The solid line composed of the closed symbols represents values from three DD6700 trials (Runs A, J, and H) at the actual measured specific energies on that refining sample while keeping intensity settings close to constant. The dotted line and open symbols represent values from three trials done on the conical refiner (Runs G, F, and C) for these similar SEL theory settings. Slight movement in the SEL parameters produced slight manipulation of output freeness measurements. The grouping tended to be much



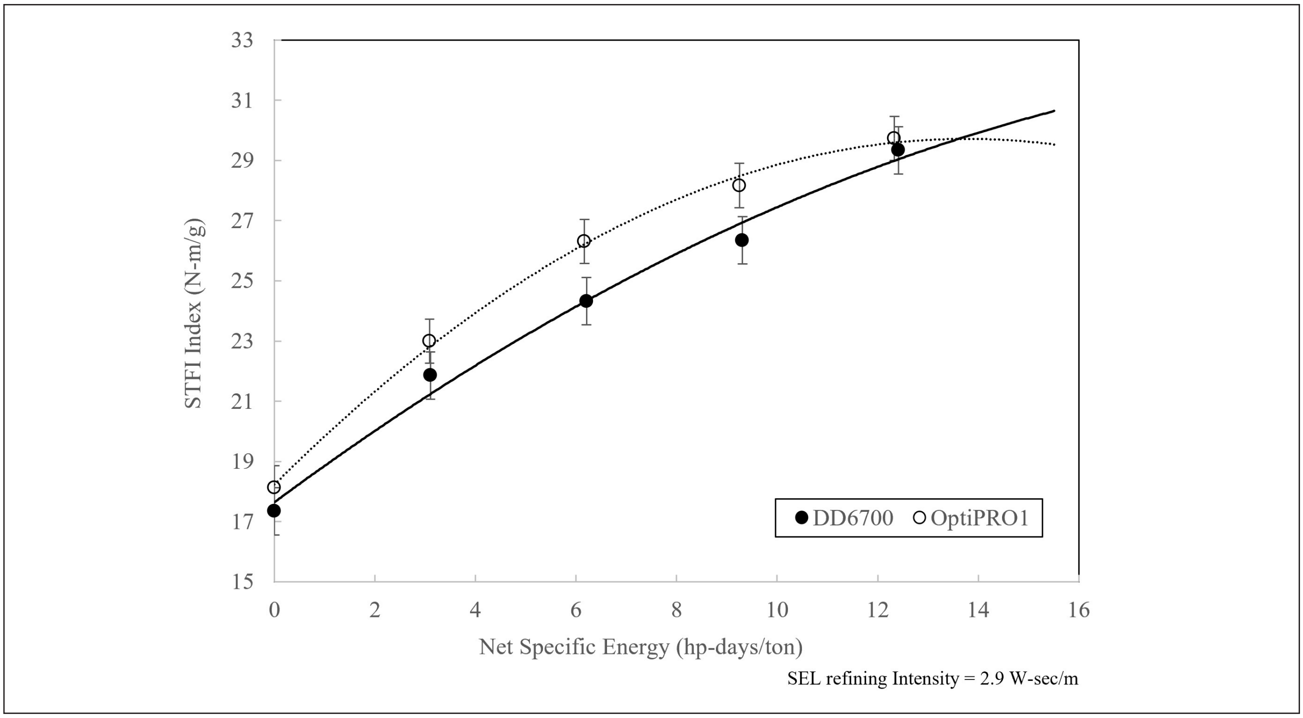
10. Freeness development at equivalent SEL intensity of 2.9 W-sec/m for the two refiner types.

tighter for the DD6700 over the Optifiner PRO conditions. A stronger diverging behavior was seen as specific energy increased from the two refiner types. Running statistical t-tests comparing the data sets in the base ply and top ply refining energy regions resulted in *p*-values of 0.240 and 0.016, respectively. At the base ply refining energy, the data was deemed statistically similar; however, as energy and divergence grow at higher refining energies for top ply refining ranges, the difference was determined to be of statistical significance, indicating SEL theory applied across these two refining types appears to be diverging on refiner type.

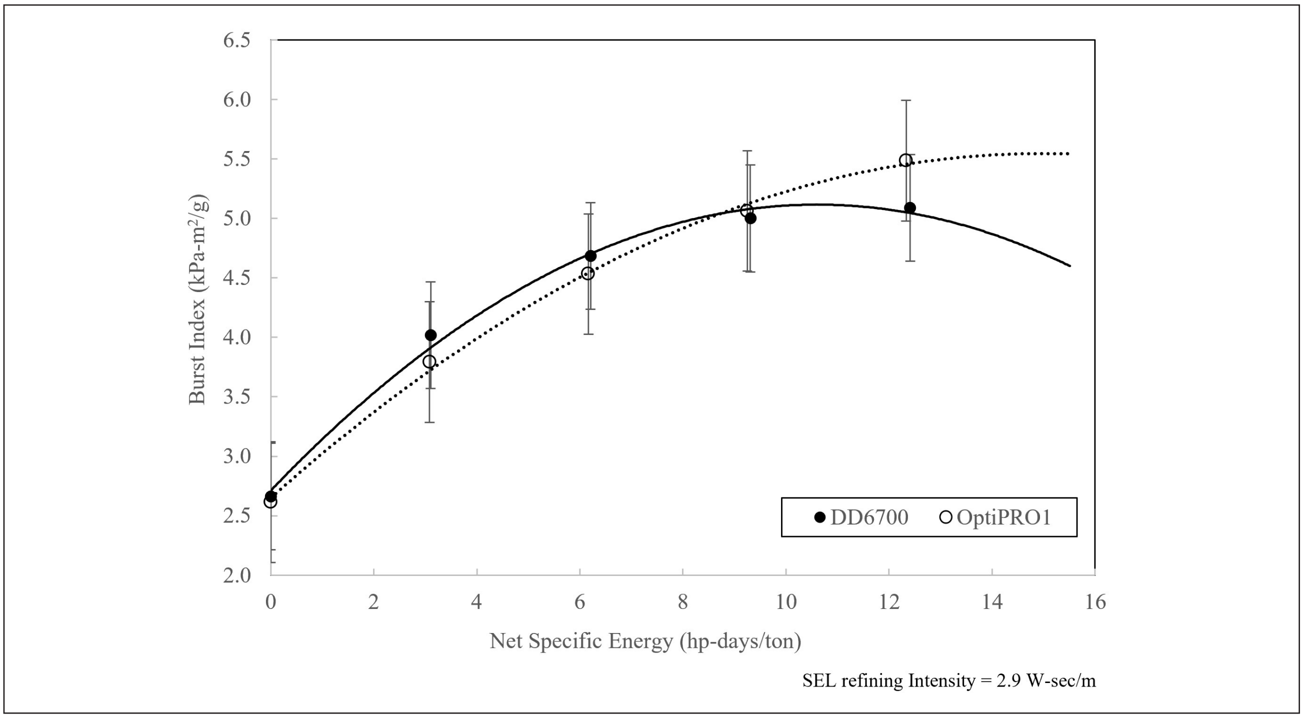
In addition to freeness development, the difference in physical properties emerged as well. **Figure 11** shows the relationship between the average STFI index compression strength and the average net specific energy among the runs. For simplicity, the runs of the DD6700 and Optifiner PRO were averaged for the remaining comparisons. The STFI is of high relevance to linerboard grades, which are often sold on this property for high performance grades. The strength parameters are represented by their respective strength indices normalized to the basis weight of the testing handsheets to minimize testing variability. In Fig. 11, it can be observed that the trendline for the conically refined pulp was consistently about 1 N-m/g higher than that of the DD refined pulp. This is consistent with the freeness data in that the conical refiner is attaining higher development at the same applied energies over the DD per applied net specific energy. Again, standard error bars were placed on this graph to show where STFI compression might be comparable for both kinds of refining. In the range of 6 hp-days/ton, a statistical *t*-test was run, producing a *p*-value of 0.000356, indicating the data sets were statistically different. This is an energy range typical of virgin kraft high kappa furnish base ply refining. The Optifiner PRO style may produce an energy advantage for generating compression strength in traditional linerboard base ply refining ranges. At the higher values approaching 12 hp-days/ton, that of typical top ply refining in linerboard, the data reconverged with little statistical difference.

Another popular paper test for linerboard remains the burst or Mullen test. **Figure 12** shows the relationship between the average burst index values and the average net energies of the double disk and conical refining runs. There is a positive relationship between the burst values and the net input energy as expected; however, significant overlap and minor difference were seen between the two refining technologies for burst developments comparing specific energy utilizing about 2.9 W-sec/m intensities. The two trend lines are concluded to be statistically similar for the energy range studied.

In addition to linerboard tests, a particular interest in common kraft bag stock properties of tear and tensile index produced were compared across refiner types. Tear and tensile are often plotted against one another to track the development properties of both as refining progresses.

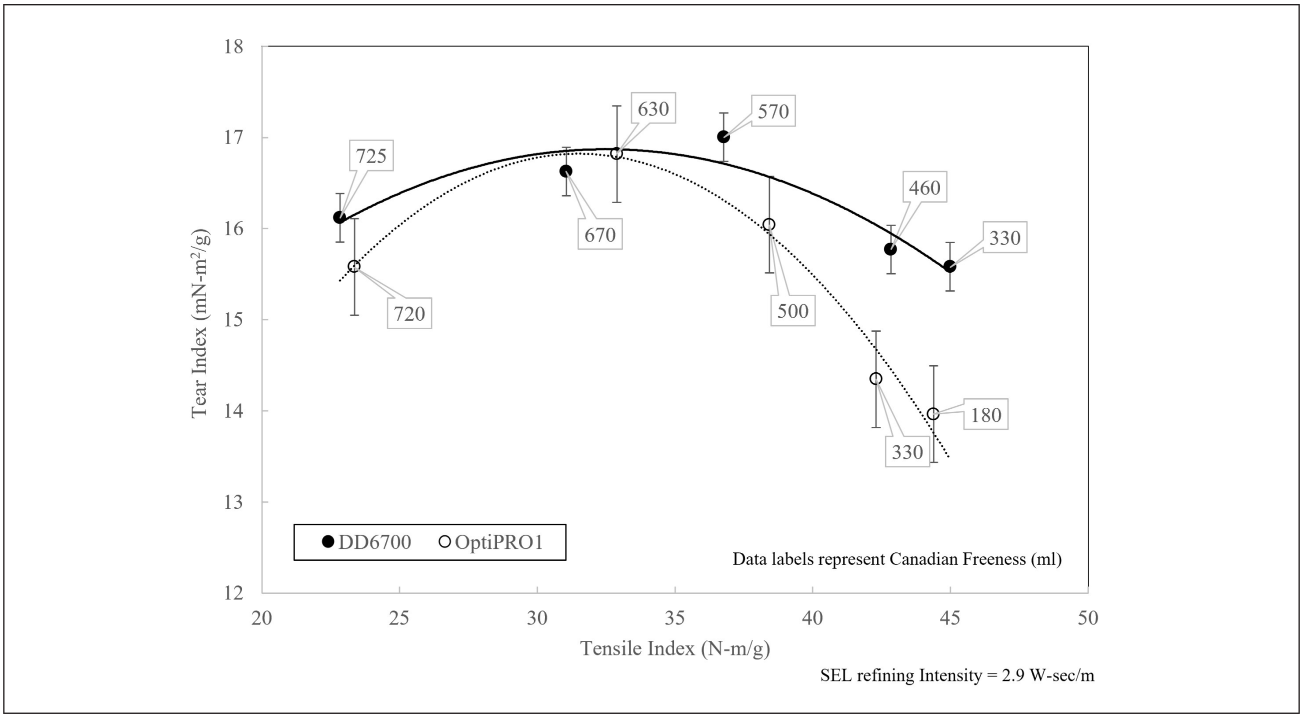


11. Compression strength index vs. net specific refining energy for the two refiner types.

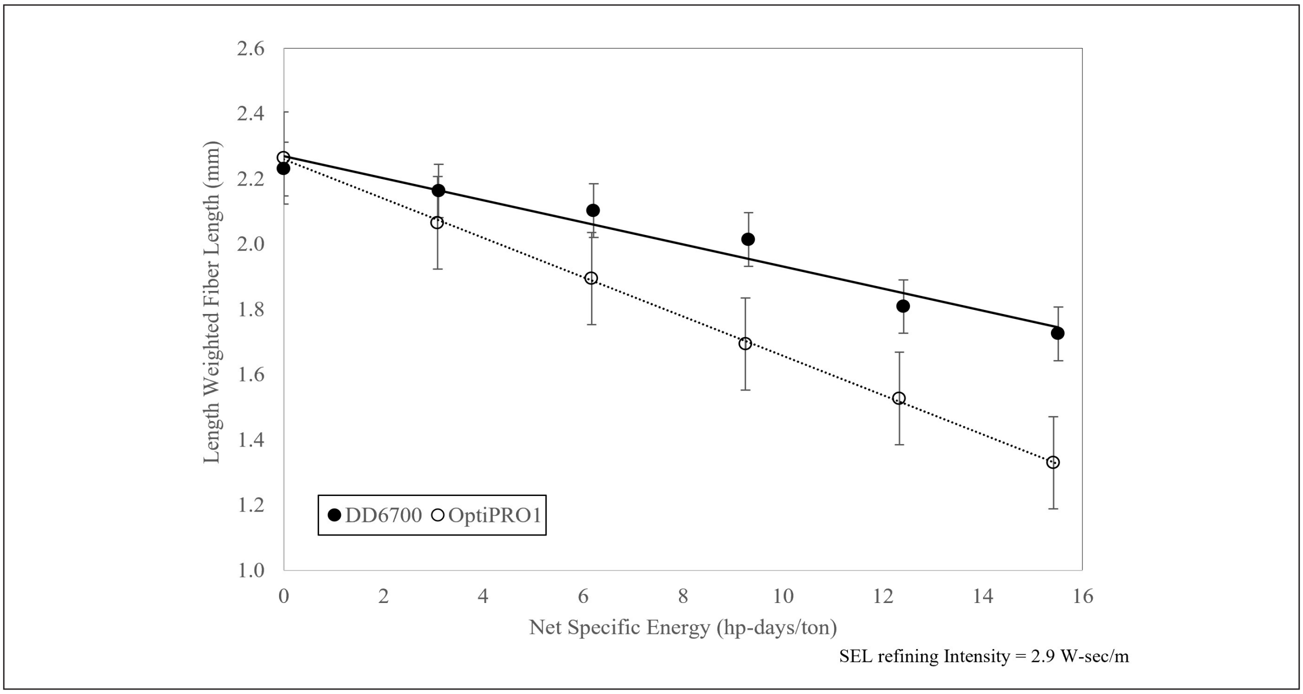


12. Burst strength index vs. net specific refining energy for the two refiner types.

Figure 13 shows the relationship between tear and tensile indices for the DD refined pulp vs. the conically refined pulp at constant refining intensity. This data also shows the corresponding average freeness value for each of the conical and DD refined pulps indicated by the data labels. It is important to pay attention to the stock freeness at desired strength values as this has direct implications on paper machine impacts, i.e., drainage and drying. Users can make comparisons at equivalent drainage if paper machine drainage and maintaining production rates are of concern. At lower input energy levels, the trends are closer together, but as the freeness drops with more specific net energy ap-



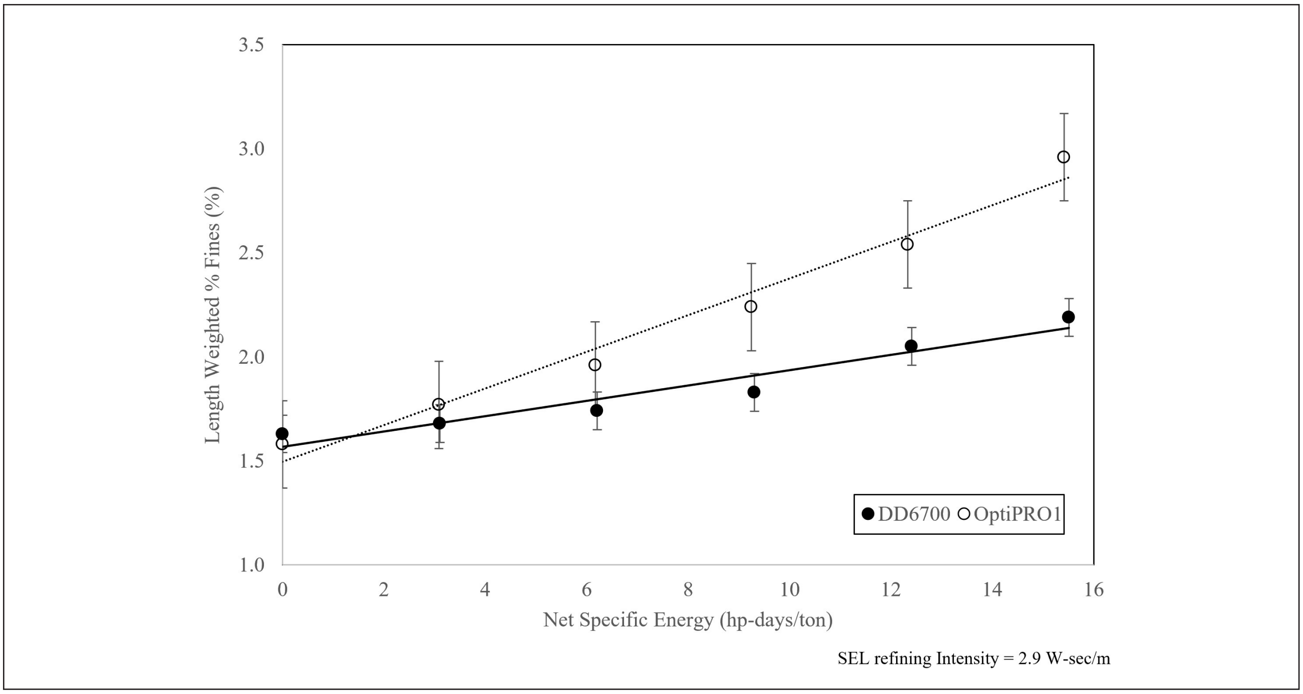
13. Tear and tensile index relationship to net specific energy applied for the two refiner types.



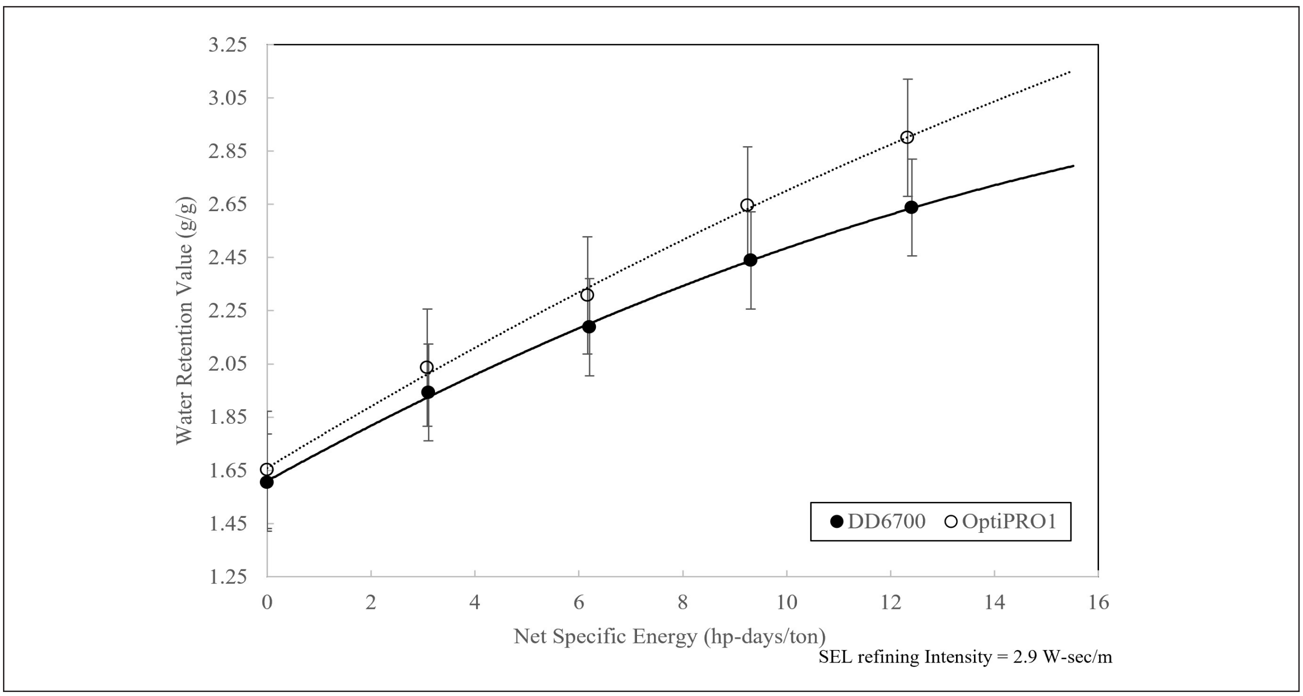
14. Length weighted fiber length development vs. specific energy applied for the two refiner types.

plied, the trendlines deviate. The double disk refined pulp maintains higher tear as the specific energy applied continues to build with statistical relevance.

Some mechanisms in tear tensile development are not explained by SEL. We further investigated to find the root cause by examining the fiber length development across refiner types. In **Fig. 14** and **Fig. 15**, the trends for the average length weighted fiber length and fines development are shown in comparison to the net specific energy input. The conically refined pulp begins to see a length weighted fiber length reduction and increase in length weighted percent fines development more quickly than the DD refined pulp, especially at higher energy levels in a diverging fashion. At these similar SEL conditions, the conical



15. Percent length weighted fines development vs. net specific energy for the two refiner types.



16. Water retention value (WRV) development vs. net specific energy for the two refiner types.

refiner appears to provide more cutting actions on the fibers and fines development than the DD refiner. This yields properties that are not necessarily suitable when wanting to build tear strength grades, but it appears favorable for building compression strength. The additional fines content may be building additional bonding but was not evident in any significant difference in burst strength. Given this difference, one would then adjust plate patterns to match refiner geometry performance to the desired grade needs on the paper machine. It does raise caution if comparing SEL settings across refiner types. Higher order theories may be needed to better interpret the results.

Finally, WRVs were measured across refiner types, as shown in **Fig. 16**. The generation of more fines as seen in

Theory	Refiner Conditions	Run A	Run J	Run H
	Rotational speed, rpm	700	756	800
	Net power, hp	217	238	251
	Refiner flow, gpm	302	330	349
SEL	Intensity, W-s/m	2.9	2.9	2.9
C-factor	C-factor number, *C*	3.40×10^{10}	3.67×10^{10}	3.88×10^{10}
	Number of impacts per mass flow through refiner, *N* (1/kg)	8.91×10^{10}	8.81×10^{10}	8.81×10^{10}
	Intensity of impacts per fiber, *I* (joules per fiber impact)	2.38×10^{-6}	2.42×10^{-6}	2.41×10^{-6}

V. Refiner theory calculations for the DD6700 double disk refiner.

Theory	Refiner Conditions	Run G	Run F	Run C
	Rotational speed, rpm	756	840	900
	Net power, hp	261	288	311
	Refiner flow, gpm	361	400	420
SEL	Intensity, W-s/m	2.9	2.9	2.9
C-factor	C-factor number, *C*	3.78×10^{10}	4.20×10^{10}	4.50×10^{10}
	Number of impacts per mass flow through refiner, *N* (1/kg)	4.15×10^{10}	4.17×10^{10}	4.25×10^{10}
	Intensity of impacts per fiber, *I* (joules per fiber impact)	5.14×10^{-6}	5.11×10^{-6}	5.15×10^{-6}

VI. Refiner theory calculations for the Optifiner PRO1 conical refiner (SEL: specific edge load).

Fig. 15 may be negatively contributing to the overall ability of fibers to shed their water in the press section. Increasing WRV would predict harder to dry fiber conditions and is often positively correlated with refining energy applied. This can be an issue if a paper machine runs dryer limited or requires more steam to hit target moisture.

Alternative theories

To investigate further these differences, additional calculations were made using traditional C-factor theories as explained by Kerekes [3], examining the *N* and *I* parameters of Eqs. 4–7 for disk and conical refiners. The C-factor represented by the number of impacts per mass (*N*) and the intensity of impacts (*I*) for the two refiner types has been calculated. **Table V** and **Table VI** show the calculated C-factor data for the DD and conical refiner geometries, respectively. Note that the SEL theory stays constant at 2.9 W-sec/m for all calculations. Across the three set points on each refining type, only slight changes in the number of impacts and intensity of impacts occur within given refiner type based on inputs for rotational speed, mass flow, power, and refining geometry.

When compared across the refiner types, the C-factor data changes while the SEL data remains constant. **Table VII** summarizes the comparisons by refiner type. Table VII shows the averages of the values in Tables V and VI by the refiner type. Running a *t*-test statistical analysis showed that the two refining types set up to achieve the same SEL results produced a statistically different number of impacts and intensity of impacts, with calculated *p*-values from the different trial conditions giving *p*-value of 0.000 and 0.000, respectively, with the conical refiner set up producing about double the impact intensities and half as many number of impacts.

Comparing the geometries of these refiners, the most notable is the single gap configuration with the plate flow through design for the conical Optifiner PRO where flow is introduced tangentially to the rotation of the rotor and exits through the stator vs. the double disk refiner twin gap formed by the floating rotor between two stator plates where flow is introduced at the eye of the refiner and flows out radially from the center of the refiner. Figure 3 represents the fiber flow path of these refiners, and the figures were provided courtesy of Valmet.

Using C-factor and the chosen plate and geometries, the Optifiner PRO was calculated at a higher intensity per

Theory		DD6700	OptiPRO1
SEL	Intensity, W-s/m	2.9	2.9
C-factor	C-factor number, *C*	3.65×10^{10}	4.10×10^{10}
	Number of impacts per mass flow through refiner, *N* (1/kg)	8.84×10^{10}	4.19×10^{10}
	Intensity of impacts per fiber, *I* (joules per fiber impact)	2.40×10^{-6}	5.13×10^{-6}

VII. Comparison of refiners using C-factor theory at constant specific edge load (SEL) conditions.

fiber impact when refiner compared to the disk refiner at SEL. The intensity impacts as calculated for the Optifiner PRO were about twice the energy of each calculated fiber impact over the DD. However, nearly twice the number of impacts were provided by the DD refiner at lower intensity impacts, which typically can impart better internal fibrillation, minimizing fiber length reductions while still improving the fiber bonding. If kraft bag production is the goal where paper is sold on tensile and tear strength properties as compared in Fig. 13, understanding the relationship of refiner geometry and proper plate selection for producing the desired results becomes of critical importance for understanding this relationship. Higher levels of intensity have often been known to provide for more cutting behavior, contributing to the fiber shorting and development of fines [15], as seen in Fig. 14 and Fig. 15. Fiber cutting is known to contribute to reduced tear strength at equivalent freeness drop and was observed in these data sets. Note that plate design can be modified to further reduce the intensity per fiber added and improve the tear strength developments for the Optifiner conical configurations.

CONCLUSIONS

This study provides a comprehensive, side-by-side evaluation of Valmet's OptiFiner PRO (conical) and DD6700 (double disk) refiners under matched SEL conditions, using high-yield southern softwood kraft. The findings demonstrate that while SEL remains a useful baseline for experimental design, it is insufficient for fully characterizing or comparing refiners of different geometries, especially when angular parameters and flow patterns significantly diverge.

Key insights

Key insights as a result of this study include:

- Batch vs. one pass mode: Batch mode refining is as effective as one-pass mode for predicting strength and fiber development in pilot-scale experiments, while offering a sevenfold improvement in trial efficiency. This supports the use of batch mode for large-scale pilot work without compromising data quality.
- Conical vs. double disk refiners: At equivalent SEL and specific energy inputs, the Optifiner PRO (conical) delivers less fiber impacts at higher intensity per impact compared to the DD6700 (double disk). This results in higher compression strength at mid-range energies for the conical refiner, while the DD refiner maintains superior tear strength and longer fiber length at higher energies. These differences are not fully explained by SEL theory alone.
- C-Factor analysis: Incorporating C-factor theory reveals that the conical refiner imparts a greater intensity of impact, leading to increased fines and fiber shortening. This mechanistic difference underpins the observed divergence in physical properties and highlights the need for higher-order theories when comparing refiner types. Plate patterns must be adjusted accordingly to avoid fiber cutting where it is not desired.

Practical recommendations

Practical recommendations based on study findings include:

- Mills seeking to optimize compression strength and energy efficiency in linerboard production may benefit from conical refiners, particularly at mid-range energy inputs.
- For grades where tear strength is critical, DD refiners remain advantageous at higher refining energies.
- Practitioners should exercise caution when using SEL as the sole basis for cross-geometry comparisons and are encouraged to incorporate C-factor or similar advanced metrics for a more accurate assessment.

Future work

Further research should focus on refining C-factor-based methodologies for tangential flow and exploring statistical correlations between plate pattern, refiner geometry, and resulting paper properties. Achieving data collapse across device types will enable more robust, predictive models for refiner selection and process optimization.

In summary, this work underscores the importance of matching refining technology to specific grade requirements and operational goals and provides actionable guidance for mills evaluating upgrades or new installations.

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ABOUT THIS PAPER

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ABOUT THE AUTHORS

We undertook this study based on 30 years of work with refining at mills and a strong belief in understanding the fundamentals of this critical operation. This study utilizes research on refining fundamentals found in the referenced papers.

The most difficult aspect of this study was applying the C-factor to different refiner types. We addressed this by pulling the theory apart and focusing on the details.

It was particularly interesting to discover the differences you can impart by refining the same pulp with different refining technology. Mills can use the information in this study as they make decisions on capital projects for refining. Our next step is to continue our work in understanding refining to maximize properties at the lowest energy.

Milne

Zou

Walker

Paulsen

Milne is staff engineer at Tighe & Bond in Portsmouth, NH, USA. Zou is senior scientist and Walker is director of the Process Development Center at the University of Maine in Orono, ME, USA. Paulsen is senior director of Research & Development at Smurfit Westrock in Richmond, VA, USA. Email Paulsen at fritz.paulsen@smurfitwestrock.com.