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Comparison of plate and conical fillings in refining of bleached softwood and hardwood pulps

Keywords

laboratory refining, intensity, softwood, hardwood, energy, swelling, bar profile

Abstract

The purpose of this study was to compare plate and conical refiner fillings in laboratory refining of softwood and hardwood pulp fibers. A better dewatering-tensile strength combination was achieved when SWK was refined with conical fillings, and the development of strength was found to be insensitive to variations in refining intensity in the range of 1.3–4.0 J/m. A bar microprofile was measured with the aid of a profilometer. The leading edges of conical filling bars were found to be rounder. A possible reason for the better tensile strength of pulp refined with conical fillings is that the round edge helps large SW fiber flocs to enter the space between the bars, resulting in less heterogeneous or more efficient treatment of fibers. The recorded gap closure values supported the above interpretation. The gap between conical fillings was found to become wider when pulp consistency and thus the tendency for fiber flocculation increased, whereas increased pulp consistency decreased the gap between plate fillings, which was further reflected as increased fiber cutting. The reduction in fiber length appears proportional to the increase in gap closure, supporting the earlier theory that fibers are squeezed and crushed between the bars. More attention should be paid to the wear of filling materials when refining long-fiber pulp. A filling material which wears so that the bar edges are rounded would seem to promote high tensile strength and high average fiber length.

Tiivistelmä

Levy- ja kartiojauhinterien vertailu – valkaistun havu- ja lehtipuunmassan kuitu- ja paperiominaisuuksien kehittyminen

Työn tavoitteena oli verrata kartio- ja levyjauhinteriä valkaistun havu- ja lehtipuunmassan laboratoriojauhatuksessa. Parempi

vedenpoisto-vetolujuusyhdistelmä saavutettiin kartioterillä ja jauhatusintensiteetin vaihtelu välillä 1.3–4.0 J/m ei vaikuttanut merkittävästi lujustasoon. Jauhinterien teräsarmien pyöreysprofiili mitattiin profilometrillä. Kartioterien johtavat teräsarmät olivat selvästi pyöreämmät kuin levyterien. Mahdollisesti pyöreämpi teräsarmä helpottaa kuituflokkien siirtymistä teräsarmien väliin, jolloin jauhatuksen heterogeenisuus vähenee tai kuidut saavat muuten tehokkaampaa käsittelyä, mikä parantaa paperin lujutta. Jauhatuksen aikana mitattu teräraon sulkeutuminen tuki yllämainittua tulkintaa. Massan sakeuden kasvaessa flokkaantuminen voimistuu ja nopeutuu. Kartioterillä sakeuden kasvu avasi teräraon, kun taas levyterillä terärao sulkeutui. Molemmilla terillä pitkäkuituisen havupuusellun kuidut katkeilivat, kun terärao sulkeutui. Levyterällä katkeilu oli huomattavasti voimakkaampaa. Jauhinterien materiaaleihin ja niiden kulumisominaisuuksiin tulisi kiinnittää viimeaikaista enemmän huomiota. Terämateriaali, jonka johtava särmä pyöristyy kohtuullisesti vaikuttaa sopivamalta, kun pitkäkuituisesta havusellusta halutaan jauhaa korkeaan lujuteen ja säilyttää kuitupituus.

Introduction

Chemical pulp fibers are usually refined in a plate- or conical-type refiner. Most often, the specific edge load (SEL) theory /1,2/, and specific energy are applied to control the refiner. In addition to the intensity and energy control parameters, the equipment type and size, the filling type and bar microprofile, the type of pulp and its flocculation tendency constitute a combination which determines the final refining result. Plate and conical refiners are generally believed to produce largely the same treatment. In some cases, conical refiners have been found to fibrillate fibers more effectively. This conclusion remains partly speculative, since the detection of the amount of external fibrillation remains unclear. In addition, it is very complicated to compare different type of refiners under the same conditions.

Plate and conical refiners differ to some extent in capacity and the proportion of no-load power. They are also somewhat different in terms of the applied refining intensity and filling dimensions; bar and groove width, groove depth and bar angle may vary slightly. Plate and conical refiners are obviously designed in different ways. Conical refiners usually have one rotating cone element, so there is only one refining zone between bars. A modern double-disc refiner has two stator surfaces on both sides of the rotor, which results in two refining zones. Two zones allow a higher energy input per refiner for a given specific edge load. Double-disc conical refiners have been recently launched in the market. Several studies /3,4,5/ have examined the role of different constructions for the final refining result. A modern conical “Conflo” refiner has a low no-load power and a long refining zone. The groove depth is shallow which decreases the no-load power arising from pumping. The fillings for this refiner tend to have a fine bar pattern, so the cutting edge length is greater than in older conical refiners. Dalzell calculated the contact area for similar conical and plate refiners and concluded that a plate refiner has a greater contact area: 20% vs. 6% /5/. Typical bar widths and groove widths of modern industrial plate and conical refiners are shown in Table 1.

It is generally accepted that the pulp flow through the refiner is heterogeneous. Inside the refiner, both untreated and well-treated fibers have been found /6/. Primary, secondary and tertiary flow in the filling groove has been detected /7,8/. The direction of centrifugal force is different in conical and disc refiners. The centrifugal force in a conical refiner creates a velocity factor whose direction diverges more from the

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Table 1. Filling dimensions and process conditions for modern industrial plate and conical refiners.

Property	Plate	Conical	Plate	Conical
	Twin Flo E	Conflo	Twin Flo E	Conflo
	SW	SW	HW	HW
Bar width (mm)	3.0 - 5.0	3.5 - 5.5	1.3 - 2.0	2.0 - 3.0
Groove width (mm)	4.0 - 5.0	4.5 - 7.0	2.4 - 3.0	3.0 - 4.0
Groove depth (mm)	4	shallow	3	shallow
SEL (J/m)	1.0 - 4.0	0.9 - 6.0	-1.0	0.3 - 1.5
SSL (J/m ²)	500 -	250 - 1000	-500	150 - 500
Consistency (%)	3.5 - 4.5	3.5 - 4.5	4.0 - 6.0	4.0 - 6.0
No-Load Power (kW)	Size and speed	Size and speed	Size and speed	Size and speed
Motor Power (kW)	Size and speed	Size and speed	Size and speed	Size and speed

primary flow in the groove. The centrifugal force directs the pulp into the grooves of the stator filling /9,10/. How this affects to the residence time or the flow pattern in the groove is not exactly known. The centrifugal force of a plate refiner is more parallel to the primary flow in the groove.

The importance of the shape and sharpness of the leading edge of the bar in the treatment of fibers is not so clear, even if different hypotheses on the importance of the leading edge have been presented. Smith noted that the leading edge of a bar is worn slightly during hollander beating, and that a very small angle is formed in relation to the leading part of the edge /11/. He concluded that the fiber layer actually protects the bars from wear. Stephansen studied the effects of the bar material by vulcanizing gum onto to the leading edge in order to confirm Smith's fibrage theory /12/. A 4-mm slice of the leading edge of the bars was removed by grinding and gum was vulcanized to the leading edge to fill the slice. The gum edge resulted in crushed and damaged fibers. Stephansen was convinced that fibers accumulate along the leading edge of the bar and that the gum edge at the bar surface was too soft to allow severe enough treatment of fibers between the gum bar and opposite metal bed plate. In the actual refining zone, which consists of the area between the narrow metal bar and metal bedplate,

the fiber mat becomes too thin to carry the load, so the fibers are crushed and treated in the wrong way. It should be noted that the process parameters in these experiments differed markedly from those in modern industrial plants. Before these experiments Stephansen /13/ had strongly stated that fibers are not cut by the leading edge but are instead broken or squeezed between the bars. The most characteristic example of such treatment is a Lampen mill, which can cut the fibers more than any other laboratory refiner. Even sharp Hollander knives never cut a fiber in the real sense of the word.

The shape of the bar leading edge appears to affect to the forces under refining. The factors affecting the shear forces under high-consistency (HC) refining have been recently examined according to a new approach /14/. This experiment revealed that the sharpness of the leading edge of the bar has a significant influence on the shear force for HC flocs of sufficient thickness, resulting in a lower tangential coefficient of friction as refiner bars are subjected to increasing wear. The development of shear force under low-consistency (LC) refining is believed to be a combination of the frictional force along the bar face and other forces associated with the bar edge. Page calls the latter forces "ploughing" friction /15/. Batchelor et al. call the same phenomenon "corner force" /16/. Ploughing force arises because the leading edge of the bars meets the fiber floc which is not compacted by the pressure from the bar edge, so the fiber material must plough through it /15/. Batchelor et al. derived equations for the corner force acting on individual fibers (F_c) and fiber flocs (F_{cf}). The equation includes the radius

of curvature of the bar edge (R_p). The actual curvature of the leading edge of the bar was not measured, but it was assumed to be 14 μm /16/. Baker classified four currently used filling materials along their bar rounding. Materials differed significantly in terms of bar edge wear /17/.

Fiber flocculation is believed to have a significant effect on the refining result when long-fiber pulp is refined /18/. Adding unrefined long fibers to a suspension of refined stock has been found to increase stock flocculation, which further increases the gap width /6,18/. Beghella and Eklund showed that the most significant parameters affecting fiber flocculation are fiber length, fiber curl index and fiber aspect ratio (length/diameter). Fiber flexibility induced by beating was found to have a minor influence on flocculation /19/. The pulp reflocculation time decreases sharply when the concentration increases /20/. The reflocculation time for SW pulp with 3% consistency varies from 2 to 10 ms, depending on the turbulence. When the consistency increases to 4%, the flocculation time is only 1 ms.

The purpose of the present study was to clarify if there are significant differences in the refining result caused by plate and conical fillings when bleached softwood kraft and bleached hardwood kraft pulps are refined, and to identify other potential parameters than refining intensity and specific energy behind the different treatment of fibers. An attempt was made to indirectly link the gap closure, the shape of the leading edge of the bar, the flocculation tendency of the pulp and process data parameters to the development of fiber and paper properties. A method to measure and calculate bar edge roundness was introduced.

Materials and methods

Refiner and fillings

A Voith laboratory refiner LR 40 was used to treat pulp fibers. The SEL theory was applied to control refining intensity /1,2/. The refiner was equipped with a process logic controller (PLC). Process data were recorded

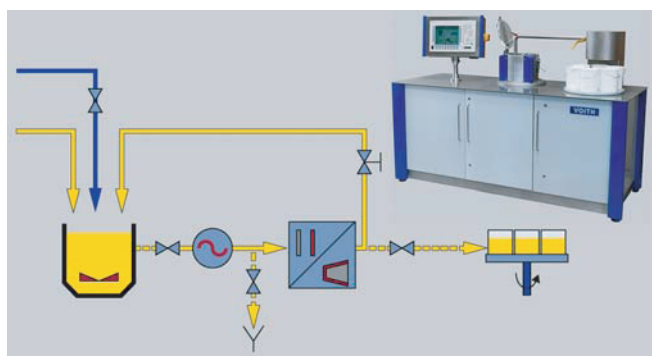


Fig. 1. Basic instrumentation and mechanical parts of laboratory refiner LR 40.

Table 2. Dimensions of fillings.

PROPERTY	PLATE	CONICAL
Bar width (mm)	3.6	3.6
Groove width (mm)	4.4	7.8 - 11.9
Groove depth (mm)	4.7	4.7
Bar angle (°)	30	30
Cutting edge length (km/rev)	0.032	0.020
Cutting speed (km/s) at 2000 rpm	1.068	0.666
Inner diameter of refining zone (mm)	85.9	83.6
Outer diameter of refining zone (mm)	145.6	128.6
Cone angle (°)	0	60

by the WinCC program. Basic trial operation and sampling were fully automatic. A Mohnopump was used to circulate the pulp from the pulper to the filling gap and back to the pulper. This gave a stable 95 l/min flow, which was insensitive to counter-pressure variations. The program calculated the correct sampling time based on the volume of pulp left in the process and the specific energy target. The main mechanical parts and instrumentation of the refiner are shown in Fig. 1.

The refiner housing included one stator filling and one rotor filling. The rotational speed of the rotor filling was 2000 rpm. The correspondent peripheral speed was 10.5 m/s at a perpendicular distance of 100 mm. The stator side moved in axial direction, controlling the motor load and thus also the gap width. One set of plate fillings and conical fillings was used, with both types having the same bar width and 60° bar angle. Filling dimensions are shown in Table 2. The fillings were made of 400 series stainless steel. The position and movement of the stator filling were recorded and the relative movement of the stator was calculated from the data. This value was used to describe the gap closure. When the trial series were run, there was no change of fillings between trials, so it was possible to compare how intensity and consistency affected the gap closure. For the plate-type filling, the relative stator movement (gap closure) was equal to the recorded value, but for the conical filling with a cone angle of 60°, the relative stator movement was calculated using Eq. (1).

$$R_c = \sin 30^\circ * R \quad (1)$$

Where R_c is the relative movement of the conical stator, and R is the measured movement of the conical stator

Shape of leading bar edge

A profilometer (Taylor Hobson, Form Talysurf Series 2) with a stylus tip was used to measure the shape of bar edges. During measurement, the stylus tip moved from the groove wall side to the bar surface side. Three bars were selected for measurement and the measurement was repeated three times for each bar. From the plate filling, both the rotor and stator edges were measured, but from the conical filling only the rotor filling was measured. Measurement data were analyzed with the Matlab software to find a numerical value to describe the roundness of the bar edge. To eliminate the micro-scale variation, the profiles were treated by a sinc-type filter, which eliminated the high frequencies from the data. The highest

point was selected from the smoothed curve. Because of the way the profiles were measured, the highest point was situated near the edge point, which is defined as the point of greatest curvature. A polynomial fourth-degree function was fitted to the part of the profile that contained the highest point of the profile as a center point in horizontal direction. From the polynomial, the derivatives of first and second orders could be readily calculated. The radius of curvature was then obtained from the Eq. (2).

$$\frac{1}{\rho} = \frac{\frac{d^2 y}{dx^2}}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}} \quad (2)$$

Pulps

A bleached hardwood kraft (HWK) and bleached softwood kraft (SWK) pulp, both produced in Finnish pulp mills were refined. Both pulps had a dry content of about 94%. The SWK was a mixture of 44% spruce (*Picea abies*) and 56% pine (*Pinus silvestris*). The HWK consisted of 97% birch. Both pulps were stored at room temperature in darkness. Handsheets of 65 g/m² were produced from the pulp according to SCAN standards. Handsheet properties were measured according to SCAN standards, except Scott internal bond strength, which was measured according to the TAPPI T833 pm-94 standard. The SR value and pulp consistency were measured according to SCAN standards. Fiber length was measured with a Kajaani FS-200 apparatus. The fiber saturation point (FSP) was measured from the whole pulp with the solute exclusion method /21/.

Experimental

Two different series were run. In the intensity series, refining intensity and specific energy were varied and pulp consistency was fixed at 5%. In the consistency series, the refining intensity of SWK was fixed at 2.8 J/m, and that of HWK at 1.0 J/m, and the specific energy and consistency were varied. Trial process parameters are shown in Table 3.

Results

Shape of leading bar edge

The radius of curvature of the leading bar edge gave a numerical description of bar edge roundness. Fig. 2 shows examples of leading edges of plate and conical fillings. The left side of the line before the circle is the groove side of the bar and the right side after the circle is the top. The average radius of curvature of the leading edges of plate bars was 36 µm, for the conical rotor average edge roundness was 214 µm. Thus, the conical rotor had clearly more rounded leading edges than the plate fillings. Batchelor et al. (1997) calculated the corner force for a laboratory refiner filling, assuming the radius of curvature of the leading edge of the bar to be 14 µm. Compared to this value, both fillings had more rounded edges.

The more rounded edge of the conical rotor filling was probably due to insufficient finishing after casting, since an unused conical rotor and stator were found to have a bent bar edge. The leading bar edges of the conical filling used in this study had probably been slightly worn during refining, causing the bent shape to become rounder. Traces of the bent edge were still found from trailing bar edges.

Refiner parameters; refining time and motor load

Since the refiner circulated pulp, the refining time increased with a decrease in refining intensity or an increase in specific energy. The decrease in refining time is illustrated in Fig. 3.

At a given refining intensity, the refining time varied due to differences in the cutting speed of the fillings. For example, at the same SEL, the refining time of the conical filling was longer, because it had a lower cutting speed. Because the pulp flow was constant at 95 l/min, an increase in refining

Table 3. Trial parameters of intensity series and consistency series.

TRIAL SERIES	SWK	HWK
Intensity series		
Filling	Plate and Conical	Plate and Conical
Intensity (J/m)	1.3 2.8 4.0	0.5 1.5
Specific Energy (kWh/t)	0, 80, 130, 180, 230, 300	0, 40, 80, 120, 160, 200
Consistency (%)	5	5
Consistency series		
Filling	Plate and Conical	Conical
Intensity (J/m)	2.8	1.0
Specific Energy (kWh/t)	0, 80, 130, 180, 230, 300	0, 40, 80, 120, 160, 200
Consistency (%)	3 4 5	3 4 5 6

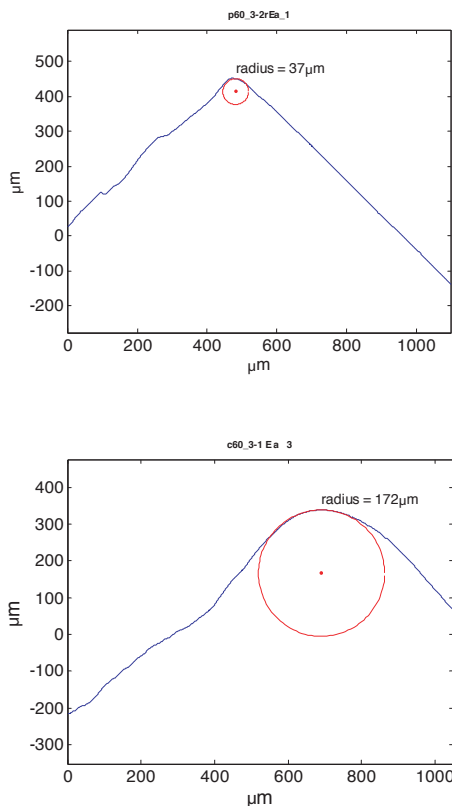


Fig. 2. Shape of leading bar edge of plate rotor (top figure) and of conical rotor (bottom figure). The Matlab software was used to calculate the radius of curvature: plate 37 μm and conical 172 μm .

time resulted in a greater number of theoretical passages of the pulp through the refiner. An increased number of passages probably resulted in a greater number of fibers treated in refining. As a result, this type of laboratory refiners as well as some smaller pilot plant refiners differ from industrial refiners because the pulp is circulated, and thus the theoretical number of passages through the refining zone becomes higher. In addition, the size of the laboratory refiner and the diameter of the refining zone is small compared to industrial refiners. Whether this significantly affects the flow pattern in the refining zone remains unclear. However, a laboratory refiner with the same operating principle and approximately the same size scale of fillings as in the Voith LR40 laboratory refiner has shown good agreement with industrial refiners /1/.

If other refining parameters are equal, but the cutting speed of the fillings differ from each other, application of specific SEL results in different applied total motor loads. For the conical filling, a SWK refining intensity of 1.3 J/m corresponded to 3 kW motor load, 2.8 J/m to 4 kW and 4 J/m to 4.8 kW. For the plate filling a refining intensity of 1.3 J/m intensity corresponded to 3.5 kW motor load, 2.8 J/m to 5 kW and 4 J/m to 6.3 kW. According to Fig. 4, an increase in refining intensity from 1.3 J/

m to 2.8 J/m with the plate filling reduced the gap by 150 μm , but when the intensity was further increased to 4.0 J/m, the gap decreased by only ten to thirty micrometers. The fact that the gap stopped closing indicates that the minimum gap was achieved, allowing only a thin fiber layer between the bars. Obviously, this fiber layer is forced to carry the load applied by the motor, and depending on the amount of fibers in the layer, the load per single fiber might exceed its resistance to breaking.

Refiner parameters; gap closure and pulp consistency

The relative stator movement (gap closure) values shown in Fig. 4 indicate that SWK fibers can be efficiently treated despite the wider-than-expected gap. The refiner gap usually varies between 50 and 150 μm /4/. Now, the difference between the maximum and minimum position of the conical and plate stator filling was about 200 μm . If it is assumed that the absolute gap width in the minimum position was 50 μm , the gap in the maximum position was $50 + 200 = 250$ μm . The tensile strength of paper achieved with the maximum gap width was found to be good.

An increase in the consistency of SWK affected the gap closure as shown in Fig. 5. Higher pulp consistency widened the gap

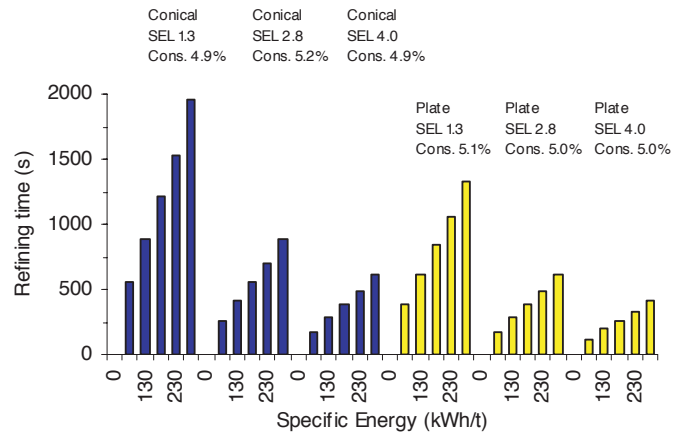


Fig. 3. Development of refining time vs. specific energy at different intensities.

when conical fillings were used. With plate fillings, the gap narrowed with an increase in pulp consistency. However, as expected, an increase in specific energy decreased the gap at every stock consistency, and with both types of filling. Only conical fillings were used to refine HWK. Less flocculating HWK behaved differently from SWK; with increased consistency the gap decreased by a few tens of micrometers, and increased specific energy did not change the gap linearly.

Refiner parameters; gap closure and fiber length

The bars in Fig. 6 and Fig. 7 depict the decrease in fiber length of SWK as a function of relative stator movement (gap closure). The fiber length decreased relatively linearly with increased gap closure. A correlation coefficient of -0.76 was calculated for the conical filling and -0.66 for the plate filling. The plate filling caused a stronger decrease in fiber length. The fiber length of HWK also decreased with increased gap closure, but the change in average fiber length of HWK was moderate, from 0.93 mm to 0.84 mm. The gap closure and fiber length results supported the earlier theory that fibers are squeezed and crushed between the bars, as suggested by Stephansen/13/.

Fiber and paper properties of SWK and HWK

The SR of SWK, as a function specific energy, increased faster when using plate fillings, indicating increased fines generation, and fiber length measurements indicated that more short fibers and fines were created by the plate filling. When specific energy increased, the FSP of SWK increased equally with both fillings. The fiber length as a function of the FSP is shown in Fig. 8. At the same FSP, greater fiber length was achieved with conical fillings. The results

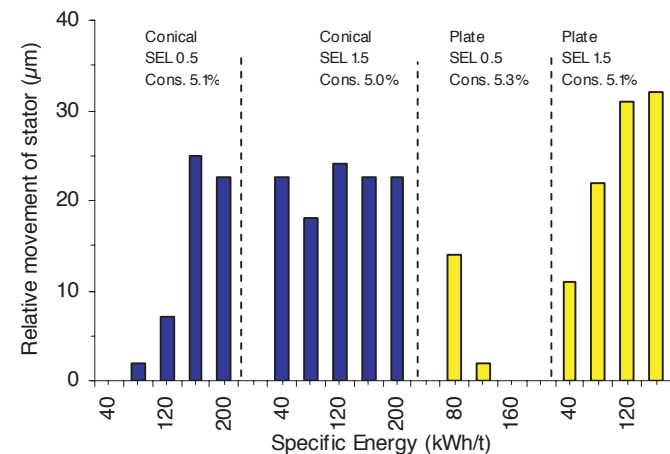
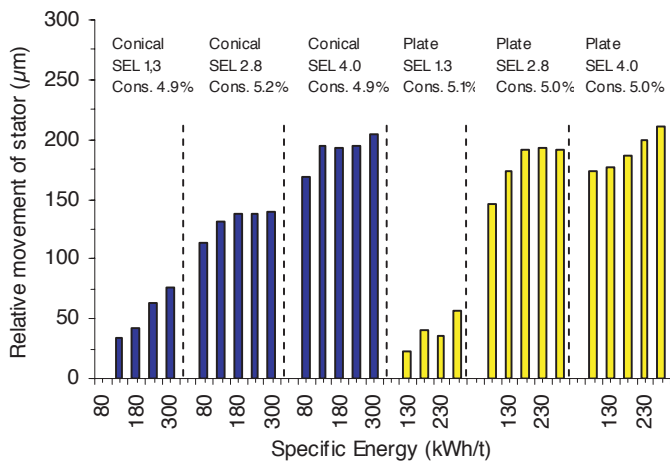


Fig. 4. Relative movement of stator filling vs. specific energy for SWK (top figure) and for HWK (bottom figure). For SWK the zero point was calculated at 80 kWh/t and 1.3 J/m, for HWK at 40 kWh/t and 0.5 J/m.

were in accord with those of Mohlin and Miller /22/, who observed that average fiber length, as a function of WRV, depended on the type of refiner.

The curves in Fig. 9 show that conical fillings gave a better dewatering-tensile strength combination for SWK. Refining intensity had hardly any effect on the tensile index of SWK when conical fillings were used. The behavior of conical fillings was unexpected. With plate fillings, increased intensity reduced the tensile index, which is a common phenomenon, as has been reported by several authors, in SW kraft refining /3,22,23/ and refining of HW, eucalyptus and deinked pulps /3,24/. Conical fillings in general produced better final tensile strength, over 80 Nm/g. With plate fillings, 80 Nm/g tensile strength was only achieved at the lowest intensity of 1.3 J/m and with a high specific energy of 300 kWh/t, though the pulp had much lower average fiber length. The dewatering-tensile index combination of HWK behaved similarly to that of SWK when the intensity was changed; high intensity and plate fillings gave the lowest tensile index, but contrary

to the SWK results, conical fillings did not produce higher general tensile strength for HWK. Less flocculating HWK behaved more in line with expectations, being less sensitive to the type of filling used.

Fig.10 shows curves illustrating the dewatering-tensile index of SWK in the consistency series. Again, conical fillings gave a higher tensile index than plate fillings. Increased pulp consistency had hardly any effect on tensile strength when the pulp was refined with conical fillings, even if the gap increased, whereas plate fillings resulted in a decreasing tensile strength trend when the consistency was increased from 3% to 4%. Fiber length was reduced in a similar way as

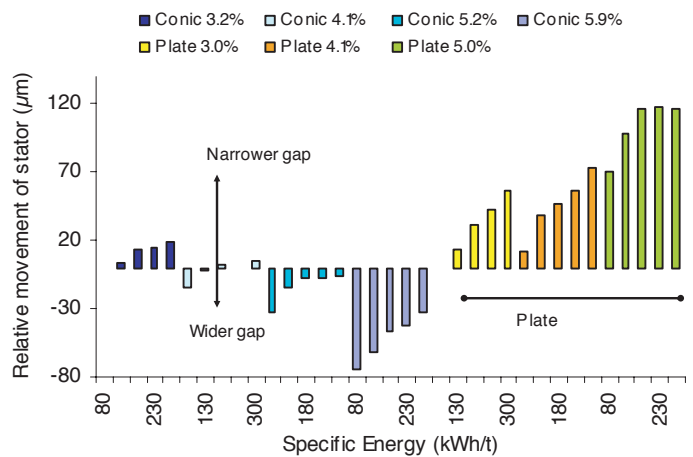


Fig. 5. Effect of SWK stock consistency on relative movement of stator.

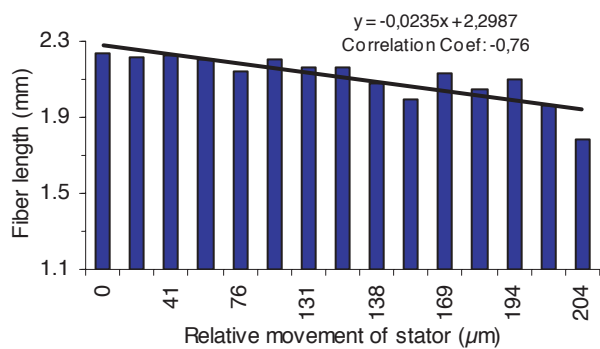


Fig. 6. Effect of relative movement of the conical stator on SWK fiber length.

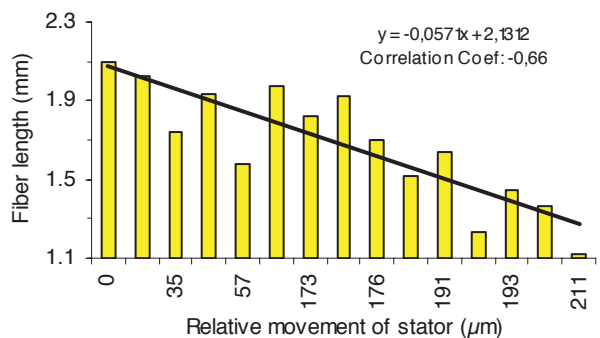


Fig. 7. Effect of relative movement of the plate stator on SWK fiber length.

in the intensity series; plate fillings resulted in more fiber cutting when consistency was increased, and simultaneously gap was found to decrease. Again, plate fillings in refining of SWK proved to be more sensitive to changes in refining parameters.

Conclusions

A better tensile strength was achieved when SWK was refined with conical fillings, and the tensile strength of the pulp was not dependent on refining intensity in the range of 1.3–4.0 J/m. Increased intensity decreased the refiner gap more steadily when conical fillings were used, and with the lowest refin-

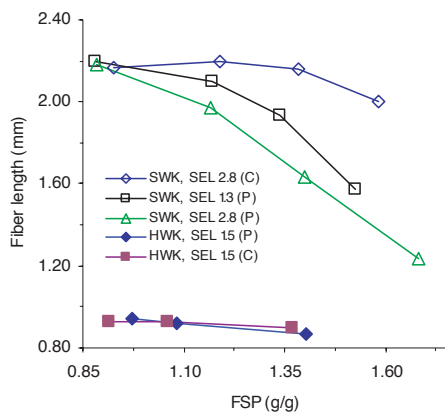


Fig. 8. Fiber length versus fiber saturation point of SWK and HWK at different refining intensities. Plate filling - (P), conical filling - (C).

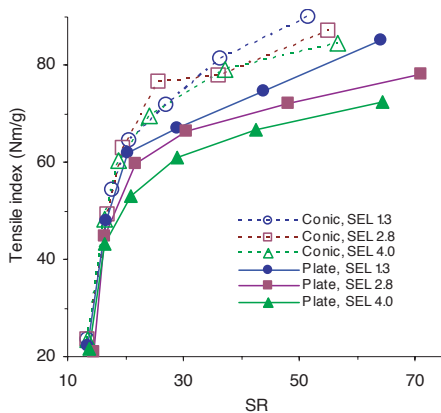


Fig. 9. Drainage resistance (SR) vs. tensile index of SWK at different refining intensities and specific energy levels.

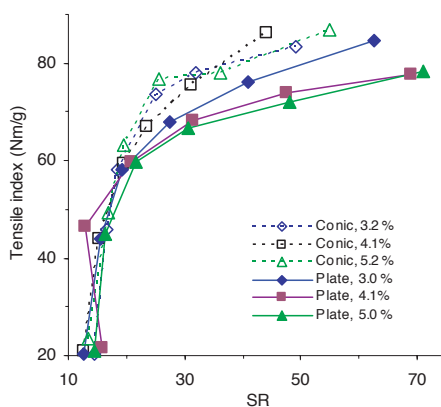


Fig. 10. Drainage resistance (SR) vs. tensile index of SWK refined with plate and conical fillings at 3-5% consistency.

ing intensity, the gap appeared to be wider than expected. However, the treatment was sufficient, since tensile strength was high. A minimum gap closure was detected for plate fillings when increased intensity and motor load no longer closed the gap, while at the same time the lowest fiber length was observed. The average fiber length of SWK appears to be proportional to gap closure. This trend was seen both with conical and plate fillings, though plate fillings decreased fiber length more severely.

The leading edges of conical filling bars were found to be rounder. This may have an important role when strongly flocculating SWK pulp is refined, since increased pulp consistency was found to lead to a wider gap with conical fillings with "round" edges, whereas with plate fillings the gap decreased. This could mean that SWK flocs could not enter effectively between the bars of the plate filling which had "sharp" edges, supporting the hypothesis that the roundness of the leading edge may affect how effectively fiber flocs penetrate between the bars. When there are fewer fibers between the bars, they seem prone to crushing and cutting.

The results suggest that fiber flocculation, gap closure and the shape of the leading edge of the bar are parameters which should be taken into account when optimizing the refining of long-fiber pulp. More attention should be paid to selecting the right kind of filling material in order to avoid wear that tends to cause sharp edges.

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