Paper technology

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The influence of bar width on bar forces and fibre shortening in low consistency pulp refining

https://doi.org/10.1515/npprj-2018-3028
Received October 23, 2017; accepted January 12, 2018

Abstract: This paper describes forces in pulp refiners and their influence on fibre shortening. We show that force per bar length obtained by a simple calculation from the Specific Edge Load (*SEL*) is a useful parameter to describe threshold force levels below which levels of fibre cutting can be avoided. Our analysis is supported by data from studies on four refiners and in one case by direct measurement of force in an operating refiner. In particular, we show that small bar widths lead to large forces and consequently that *SEL* must be adjusted to lower levels to avoid fibre cutting. We also speculate on the lower limits of bar width.

Keywords: bar forces; bar width; fiber shortening; pulp refining; Specific Edge Load.

Introduction

We begin by describing the overall picture of energy and intensity in low consistency pulp refining. The most common parameter to measure refining action is the Specific Refining Energy, E. Being a cyclic process, refining energy is made up of two components, the number of impacts seen by pulp, N, and the intensity, of each impact, I. Their product is energy i. e.

$$E = N \cdot I \qquad (1)$$

As illustrated in Figure 1, differing combinations of N and I for a given E produce different effects on pulp.

Any two of the variables in Equation 1 determine the value of the third. It is common to use only energy and intensity.

The most commonly used measure of intensity is the Specific Edge Load (*SEL*). This was developed in Germany

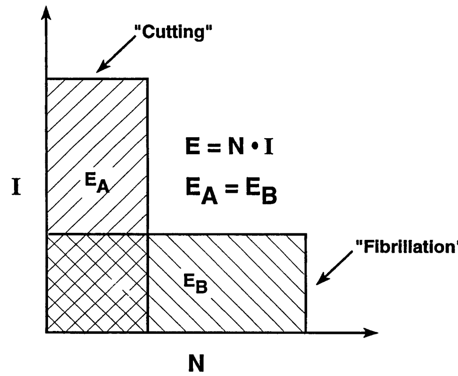

Figure 1: Illustration of Specific Refining Energy as the product of number and intensity of impacts on pulp (Kerekes 1990).

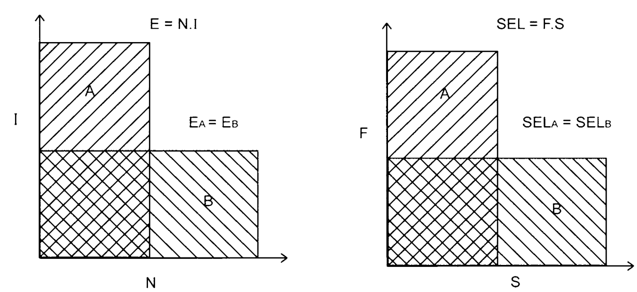

Figure 2: Illustration of Specific Edge Load (SEL) as the product of bar force and sliding distance over which force is excerted, analogous to energy factored into number and intensity of impacts (Kerekes 2015).

(Brecht and Siewert 1966) based on a logical approach to describe how power is distributed among bar crossings during refining. Later, additional variables were accounted for by a Modified Edge Load (Meltzer and Rautenbach 1994). Although derived empirically, *SEL* can be derived from first principles and shown to have a rigorous scientific meaning as the energy expended per bar crossing per bar length. This derivation presented in Kerekes and Senger (2006) is reproduced in the Appendix.

Given this definition, the *SEL* can be factored into the product of two variables that govern energy expended by a moving body. This is force F multiplied by the distance of movement during which force is exerted, s. Thus $SEL = F.s$. In essence, this factoring is analogous to the factoring of energy above and is illustrated in Figure 2.

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We now consider the effect of these variables on pulp properties. Internal fibrillation is produced by breaking molecular bonds. Such breaking is created by imposing strain on fibres, and these are produced by forces. Excessive strain from excessive force produces fibre shortening. On the other hand, external fibrillation is produced by abrasion. This property is governed by energy expended by one body sliding over one another. In summary, force, not energy, is the key variable for two of the three main refining results. In this paper we focus on fibre shortening.

Analysis

As described above, we may express bar force F as

$$F = \frac{SEL}{s} \quad (2)$$

We note here that when s is the bar width, F is similar to the Specific Surface Load (SSL), developed by Lumiainen (1990). The SSL was developed as an empirical modification to the SEL to account for the fact that power is expended over the width of a bar rather than just at its edge as implied by the SEL. Our derivation has shown that SEL is in fact energy per bar length and consequently that F is the force per bar length in the direction of bar movement.

If we assume an effective coefficient of friction μ, we may estimate the pressure P acting on bar surface as

$$P = \frac{SEL}{\mu s^2} \quad (3)$$

Further aspects of this derivation are described in Kerekes (2011)

A key question is the size of s. If bar width W is larger than a fibre length l (i. e. $W > l$) most of the pressure is exerted over a zone of about a fibre length, as shown by Goncharov (1971). Thus, $s = l$. On the other hand, if bar width is smaller than a fibre length, i. e. $l < W$, bar width, not fibre length, determines the zone of pressure. In this case $s = W$. For fibre length l, we employ the length-weighted average length throughout this study.

Although greatly simplified, this analysis appears reasonable in light of current knowledge. For example, Baker (1995) recommended $SEL = 2\,J/m$ for softwood and $SEL = 0.2\,J/m$ for hardwoods. Assuming a coefficient of friction $\mu = 0.1$, and bar width larger than a fibre length and $l = 2.5\,mm$ for softwood and $l = 0.8\,mm$ for hardwood, equation (1) gives $P = 3.2\,MPa$ for softwoods and $P = 3.1\,MPa$ for hardwoods. This pressure range is similar to findings of Nordman et al. (1981) who found in compression tests that a pressure of 2–4 MPa was required to produce effects similar to those achieved in refining. In refining sulphite chemical pulp, Goncharov (1971) measured peak pressure of 3–4 MPa for $SEL = 1.5\,J/m$, and a coefficient of friction $\mu = 0.11$.

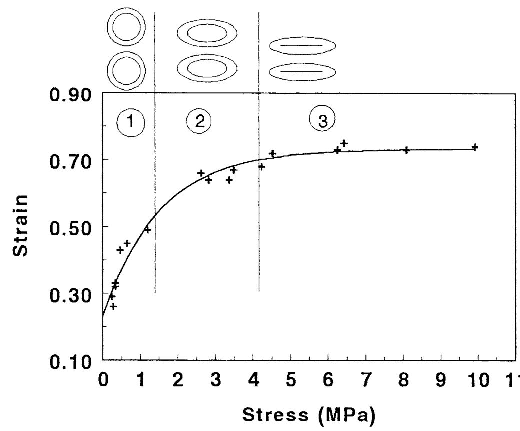

Figure 3: Fibre compression (from Amiri and Hoffmann 2003).

The likely reason for a desirable pressure around $3\,MPa$ is that fibres are strained in compression to a plateau level beyond which there is little further strain and consequently internal fibrillation. This is illustrated in Figure 3 taken from a study of dynamic compression of pulp mats by Amiri and Hoffmann (2003).

Fibre shortening

The use of pressure as an intensity is useful for internal fibrillation and making comparisons to other published work, but it is not the key factor in fibre shortening. Page (1989) found that fibres are shortened in refining by tensile failure, not by a scissor-like cutting or compression. Accordingly, shear force is the key variable for fibre shortening. Estimates of such forces on individual fibres in refiner gaps have been made by Kerekes and Senger (2006). Later, Berg et al. (2015) successfully predicted fibre shortening in an LC refiner. However, doing so at the fibre level requires measurement of the gap size between bars, a difficult and rarely made measurement. Accordingly, our objective in this study is to use a force that does not require this measurement. We therefore focus on bar force, F.

Bar shear force is made up of two component forces. Batchelor et al. (1997) showed these to be the sum of a corner force F_c and a surface friction force F_s,

$$F = F_c + F_s \quad (4)$$

They found the relationship of these two forces to the force normal to the bar surface, N, to be

$$F = \mu_c N^{5/3} + \mu_f N \quad (5)$$

The term μ_f is the coefficient of friction cited earlier. The coefficient μ_c is a complex parameter influenced by many variables, including, consistency, fibre length, fibre diameter, fibre modulus of elasticity, fibre Poisson ratio, as well as some empirical factors. The key bar variable, and perhaps the dominant variable, is r, the radius of curvature of the bar edge, i. e. the bar edge sharpness. This dependence can be shown from Batchelor et al. (1997) to be of the form

$$\mu_c \propto \frac{1}{r^{0.33}} \tag{6}$$

Clearly, as r becomes small, that is as bars become sharp, μ_c becomes very large and therefore dominates F. Koskenhely et al. (2007) showed the best levels of r to be in the range 80–150 μm and severe fibre shortening to start in the range 30–50 μm.

Given the complexity of these factors and our limited knowledge, we are not able to model the corner force in detail. Nevertheless, we must account for ploughing shear force at the edge. We do so by recognizing that as bar edges with fibres stapled upon them approach one another, shearing force begins before the bar edges actually cross, In effect, this adds to distance s of the shearing zone. Accordingly we consider a total shear length to be the sum of the distance at the edge, s_c plus the distance on the bar surface, s_s, giving $s = s_s + s_c$.

We now estimate the size of s_c by considering fibres stapled on bar edges to be drawn from a zone of size l^2 in a groove, with l being fibre length, and at consistency C. We estimate this amount of pulp to be compressed at the gap entry to a consistency about the level in a gap, which is about 20 %, the consistency which supports a pressure of about *3 MPa*. (Kerekes and Senger 2006). Thus, the mass balance is $0.2s_c l = Cl^2$ giving $s_c = 5Cl$. As an example, for a fibre length of 2.5 *mm* and suspension consistency of 4 %, s_e = 0.5 mm, which is about 20 % of the fibre length. As bar width becomes small, this edge effect becomes a large factor in determining force. Clearly, this estimate is only approximate, but it appears to be a reasonable one.

We now define s_s as the zone over the bar surface. When bar width is larger than a fibre length $s_s = l$, and when it is smaller than a fibre length $s_s = W$. Summarizing the above considerations, we have

$$F = \frac{SEL}{s} \tag{7}$$

$$s = l + 5CL \quad when\ W > l \tag{8}$$

$$s = W + 5Cl \quad when\ W < l \tag{9}$$

We may note the implication of the above for a lower limit of bar size. In the limit, as bar width approaches zero, i. e. $W = 0$, bars become sharp blades, meaning $s_s = 0$. Thus $s = 5Cl$. In short, even if there is no bar width to support shear, fibres drawn into the gap by sharp edges will create a small zone that can support a shear force. Distance "s" will only decrease to zero and force increase to infinity if no fibres are captured from the groove. This occurs when $W = 0$ and either $C = 0$ or $l = 0$.

Materials and methods

Our experimental program consisted of two dedicated laboratory studies on NBSK market pulp donated by Canfor Pulp Products, a third study of measured forces reported in a recent publication in the literature, and data from an earlier doctoral thesis.

Study A was carried out at PTS (Papiertechnische Stiftung) on a 12 inch single disk laboratory refiner using 3 sets of plates custom fabricated for this study. Bar widths were 4.2, 2.0, and 1.0 mm. For each plate, groove width was approximately 6 mm and groove depth 4 mm. Bar angle was 39 degrees. The tests were carried out by circulating pulp through the refiner loop. Unrefined fibre length was 2.47 mm. All lengths were measured on a Valmet FS5 instrument.

Study B was carried out on a Voith 20 inch TwinFlo refiner. Bar width and groove width were 1.5 mm and 3.8 mm. Groove depth was 5 mm. Bar angle (defined here as the average angle of the bars of a segment to the radius) was 30 degrees. Tests were carried out in a chest-to-chest mode. Unrefined fibre length was 2.55 mm. All lengths were measured on a Valmet FS300 instrument.

Study C was taken from force measurements reported in a recent publication (Harirforoush et al. 2017). The measurements were made by a force a sensor which replaced a short segment (5 mm) of a bar length on an operating Aikawa 16 inch single disc refiner at the University of British Columbia. Bar width, groove width, and groove depth were 1.6 mm, 3.2 mm, and 4.8 mm. Bar angle was 15 degrees. The pulp was a high- freeness (378 CSF) TMP from northern British Columbia having average initial fibre length of 1.85 *mm*.

Results and discussion

Study A

We first examine the effect of intensity on fibre shortening at $SEL = 1\,J/m$ in Figure 4. Bar forces are also shown

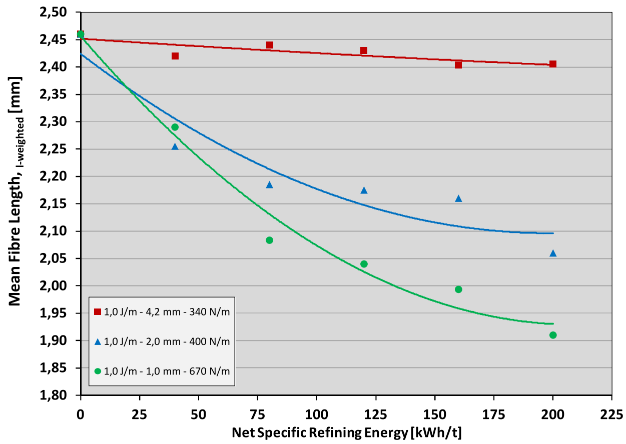

Figure 4: At same SEL = 1 J/m, bar forces over 300 N/m gives large fibre length reduction.

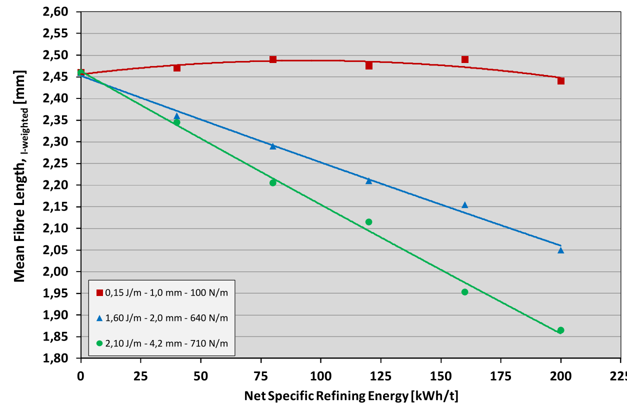

Figure 6: For bar widths 4.2, 2.0, 1.0 *mm* and *SEL's* 2.1, 1.6, 0.3 *J*/*m*, large length reduction occurs between bar forces 100 and 640 N/m.

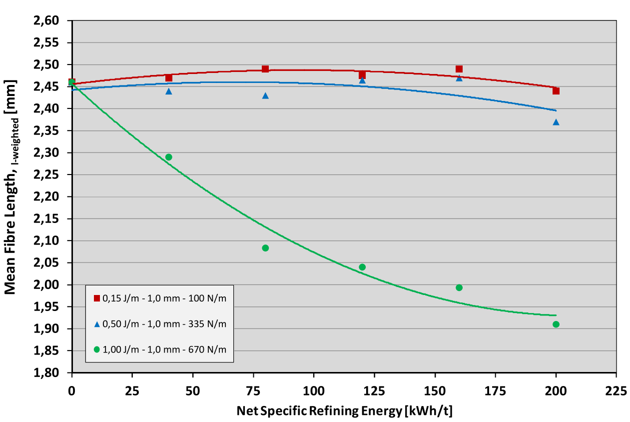

Figure 5: At the same bar width of *1 mm*, large length reduction takes place between 335 and 670 N/m.

for each case. It is apparent that smaller bar width gives a larger bar forces and greater fibre shortening. Over the force range 340 to 670 N/m a large reduction in fibre length occurs in the range 330 to 400 N/m.

We next examine the effect of decreasing *SEL* from 1.0 *J*/*m* to low levels of 0.5, and 0.15 *J*/*m* at a constant bar width of 1 *mm*. These data are shown in Figure 5. The corresponding bar forces are 670, 335, 100 *N*/*m*. As shown in Figure 5, for *SELs* below 0.5 *J*/*m*, that is, forces at and below 335 *N*/*m*, the loss of fibre length is quite small.

All cases discussed thus far have been for a small bar width of 1 *mm*. We next examine larger bar widths up to 4.2 *mm* and *SELs* up to 2.1 *J*/*m*. As shown in Figure 6. a significant length reduction begins at a bar force somewhere between 100 and 640 *N*/*m*.

The data in Figures 4, 5, and 6 show a strong dependence on energy as well as intensity. This is expected because at a given intensity, energy reflects the number of bar crossings to which pulp is exposed. Refining is a probabilistic process and therefore length reduction depends on both number and intensity of the impacts. In the data of Figures 4, 5, and 6, in most cases there is a near-linear dependence of length loss on energy over most of the range. Of particular interest, when force around 300 *N*/*m* or less, there is little or no length reduction, even at high energy of 200 *kWh*/*t*.

Comparisons with results from studies B and C

We next compared the above findings to data from studies B and C. For clarity, we normalized fibre lengths to the unrefined length and compared data at a common specific reefing energy of 160 kWh/t. The results are shown in Figure 7.

The data in Figure 7 show a significant difference between Studies A and B. Our other data, not reported here, generally fall between the data of A and B. Such scatter is not surprising given the differing sources of data and the many factors described earlier that are not accounted for, such as bar edge sharpness. Thus A and B may be regarded as an "envelope" of bar force for this energy case i. e. 160 kWh/t. Given that the experimentally measured force from Study C is in good agreement with the data of Study A, we may regard this as a lower limit of force for a given length reduction at this energy, or expressed another way, a maximum force to ensure that a target length reduction is not exceeded.

We now consider some example applications of these findings. To ensure less than 10 % loss in fibre length, bar force should be no more than about 500 N/m. For zero

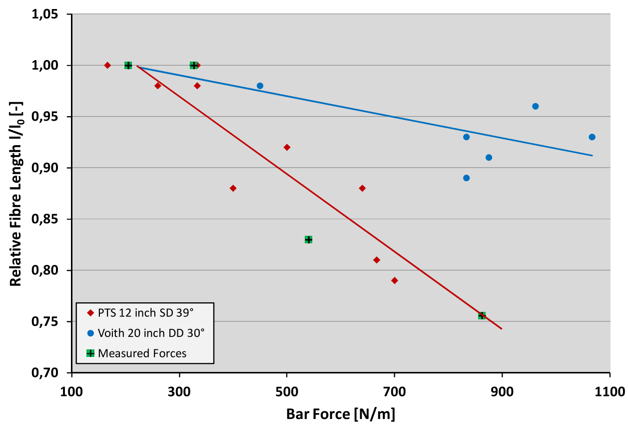

Figure 7: Data from Studies A and B for refining energy 160 kWh/t show an envelope of fibre shortening and bar force. Data measured by a force sensor fall near the Study A line.

length reduction, the intercept in Figure 7 suggests a force level of about 200 N/m. Study B indicates that this target level of length reduction may be met at higher forces, but we do not have enough knowledge to specify the conditions when this may happen. In summary, a force below the lower limit of the envelope ensures the target level is met, but does not imply that higher forces may not do so.

Another example is setting the *SEL* level. For an NBSK fibre of length 2.5 mm and bar width larger than 2.5 mm, *SEL* should be no more that 1.5 J/m to ensure less than a 10 % length loss. For a bar width of 1 mm, *SEL* must be lowered to less than 0.75 J/m to meet this objective.

We note here that both of the above examples are for SRE = 160 kWh/t. As indicated in Figures 4 to 6, lower energies at any SEL or bar force decrease the level of length reduction. On the other hand, for bar force less than 200 N/m, there will be little or no length reduction even at a high energy of 200 kWh/t.

Conclusions

The major conclusions from this study are:

1) *SEL* on its own is insufficient to characterize refining intensity when bar width is less than a fibre length.
2) Bar force calculated in a simple manner from the *SEL* is a useful parameter to establish intensity levels that ensure fibre shortening does not exceed a target level at a given energy.
3) The simplicity of the force calculation and the complexity of the many factors affecting fibre cutting do not permit predictions beyond the above, but the approach shows sufficient promise to justify further study to incorporate additional key variables

Funding: We gratefully acknowledge and thank Canfor Pulp Ltd for providing financial support to conduct studies A and B.

Conflict of interest: The authors declare no conflicts of interest.

Appendix

Derivation of the Specific Edge Load (reproduced from Kerekes and Senger 2006)

The Specific Edge Load (*SEL*) of a refiner is defined as the net power *P* divided by the bar edge length (*BEL*) multiplied by the rotational speed, ω, where ω is in rotation per second:

$$SEL = \frac{P}{BEL\omega} \tag{A1}$$

BEL is determined empirically in the following manner for a disc refiner. The radius is divided up into a number of small length segments. The number of bars in each segment is counted for the rotor and stator and then multiplied together. This product is multiplied by the size of the segment and the resulting values are added up over the full radius to obtain the *BEL*. Below we derive the *SEL* directly by calculus.

We consider a circle in the refiner of radius, r, and the number of bars on the rotor to be n_r and stator to be n_s. Thus, the total number of bar crossing after one full rotation is $n_s \cdot n_r$. Assuming that $n_s = n_r$, and expressing these in terms of bar density, n, which is defined as the number of bars per unit arc length, we obtain $n_s = n_r = 2\pi rn$. Therefore $n_s \cdot n_r = 4\pi^2 r^2 n^2$ for one rotation. The rate of bar crossings is therefore $4\pi^2 r^2 n^2 \omega$ where ω is in rotations per time.

We next multiply these crossings by incremental radial length, in this case dr, and then sum these up over the radius of the refiner from R_1 to R_2 to obtain *BEL*.

$$BEL = \int_{R_1}^{R_2} 4\pi n^2 r^2 dr = 4\pi^2 n^2 \frac{R_2^3 - R_1^3}{3} \tag{A2}$$

We now consider power consumption. We start with energy consumed per bar length per bar crossing, E_b. Thus, the energy over dr is $E_b dr$ This energy expressed in polar coordinates is torque T, multiplied by the angle

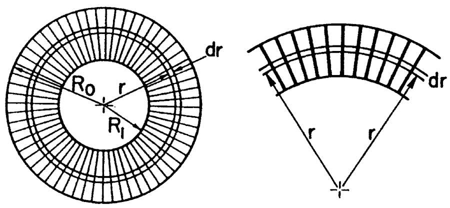

Figure 1A: Schematic of refiner plate.

through which rotation takes place, θ, i. e. $E_b = T\theta$. We may express torque as the product of force F multiplied by radius r, and θ as $\theta = a/r$ where a is the arc length of rotation over one bar. This gives $E_b = F \cdot a$. Because bar widths are very small, we can assume that a is simply the linear distance over the bar width, which we call the sliding distance. We note here that E_b, T and F are all for unit radial length. Thus we obtain the energy expenditure for one bar crossing in increment dr as

$$E_b dr = F \cdot dr \cdot s \tag{A3}$$

The energy consumed by all crossings the annulus dr after one rotation, dE, is therefore:

$$dE = E_b 4\pi^2 r^2 n^2 dr \tag{A4}$$

The rate of this energy expenditure, power dP, is

$$dP = E_b 4\pi^2 n^2 r^2 \omega dr. \tag{A5}$$

It is apparent that when dP is integrated from R_1 to R_2 we obtain

$$E_b = \frac{P}{BEL \cdot \omega} \tag{A6}$$

Thus, from A1 and A6, $E_b = SEL$ and from equation (2) $F = SEL/s$.

We note an important assumption of this analysis is that E_b is constant throughout the refiner. It therefore represents an average value, as does the SEL.

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