Force-based characterization of refining intensity

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KEYWORDS: refiners, pulp refiners, mechanical pulping, refining intensity

SUMMARY: This paper describes a force-based refining intensity applicable to high and low consistency refiners. The intensity is based on forces on bars determined from refiner power, tackle, and operating conditions. Bar forces are linked to forces on fibres through fibre distribution over bars and gap size. Predictions of forces from this intensity were compared to forces measured in a high-consistency primary refiner, reject refiner, and a low-consistency refiner in mechanical pulping. The predicted and measured forces were in good agreement for the reject and low consistency refiner, and somewhat less so for the primary refiner.

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Various approaches have been taken over the years to quantify refining action by a refining intensity. Separate approaches have been taken for high consistency and low consistency refiners, but it would be useful to have a common approach to enable comparisons. Further, it would be useful to have intensities that are directly linked to the key variable causing the refining effect – forces on fibres.

A major difficulty in characterizing intensities at high and low consistencies is the vast difference in rheological behaviour. Low consistency (LC) (3-5%) pulp suspensions are continua that fully fill a refiner. Consequently, bar crossings provide a reasonable measure of loading cycles on the pulp mass. Intensity at the fibre level can be determined from mass balances and probabilities of fibre impacts at bar crossing events. Leider and Nissan (1977) and later Kerekes (1990) developed approaches to estimate intensities in terms of energy per mass per impact.

At high consistency (HC) (20-40%), pulp suspensions are heterogeneous, compressible, three-phase mixtures. Indeed, the amount of fibre in the refiner is not known. The motive power to force fibre through the refiner is supplied by the refiner itself, specifically from the centripetal force caused by disc rotation. To obtain a refining intensity in this case, Miles and May (1990), and later Miles (1991) employed a force balance to estimate the residence time of pulp, and from this, obtained the number of impacts on pulp. Dividing specific energy by this number, they obtained an intensity in terms of specific energy per impact. This was a significant step forward in the science of mechanical pulping. Miles (1990) proposed a second parameter for intensity, a “specific refining power”, defined as power expended by the refiner divided by the mass of pulp in the refiner. Miles attributed the importance of this parameter to the rate at which energy was applied to the pulp.

The above approaches are energy-based intensities. They all fall short in some respects. In the case of high consistency mechanical pulping, Murton et al (2002) have shown that gap size is the overriding factor governing pulp quality. In low consistency refiners, refining, Mohlin (2006) has shown a strong dependence on gap size. Energy-based intensities do not account for gap size. This observed dependence on gap size dependence suggests that forces are critical.

As described by Kerekes (2010), moving bars impose forces on fibres during bar crossings through a balance of equal and opposite forces on bars and fibre. Forces on fibres produce the strains which cause the refining effect. The opposing force on bars produces the torque we measure as power input to the refiner. Bar forces multiplied by distance of bar movement during application of this force represent the energy consumed during a bar crossing. The total of these crossings is the energy expended, which is the energy we measure. But this is not the energy expended in internal strain in fibres. It is therefore not directly linked to fibre flexibilization, a key objective in refining chemical pulps. In contrast, in mechanical pulping new surface creation by removal of surface material is of key importance along with flexibilization. This surface removal is a process of abrasion which is strongly linked to energy expenditure by bar movement. The constraint is fibre shortening, which is governed by forces on fibres (Kerekes 2010).

In summary, force, not energy, is the key link between bars and fibres in refining. It is the causal variable that produces key changes in fibre properties. This suggests that force may be more suitable than energy as a basis for refining intensity. The objective of this study is to develop a force-
based intensity of refining which is applicable to both low consistency and high consistency refining.

Analysis
Specific Edge Load
The Specific Edge Load (SEL) has been widely used for many years to characterize refining intensity in low consistency (3-5%) pulp refiners. Developed empirically by Wultsch and Flucher (1958) and Brecht and Siewert (1966), the SEL is defined as the power supplied to the refiner divided by the product of the number of bars on the rotor, the number of bars on the stator, the length of working zone, and the rotational speed. In recent work, Kerekes and Senger (2006) showed rigorously that SEL represents energy expended per bar crossing per unit bar length. Thus, SEL is a “machine intensity” or “bar intensity”, meaning it represents the energy expenditure at bar crossings without reference to how this energy is distributed to pulp. As a descriptor of “bar energy”, it is applicable to both high consistency and low consistency refiners. However, the effect on pulp differs between these two consistency ranges.

At low consistency (3-5%), the SEL gives a reasonable approximation of action on pulp because the refiners are completely filled with pulp. In contrast, at high consistency (20-40%) refiners are only partially filled with pulp. The pulp is suspended non-uniformly in a steam-air mixture and is in a very compressible state. Consequently, the link between SEL and action on pulp is much less clear. Nevertheless, if the limitations on the link between SEL and action on pulp in high consistency refiners are understood, there is no reason why SEL cannot be used as a machine intensity for high consistency refiners.

Forces on Bars
Kerekes and Senger (2006) showed that the SEL may be factored into a shear force per unit bar length in the direction of bar motion, \( F_B \) and distance of bar travel \( s \) during which this force is exerted. For the simple case of zero bar angle, we obtain:

\[
F_B = \frac{\text{SEL}}{s} \tag{1}
\]

Further discussion on calculating the SEL is given later in this paper.

The normal bar force, \( N_B \), can be related to the shear force by an “equivalent coefficient of friction”, \( \mu_e \), which combines the corner force and friction force (also discussed later). This gives:

\[
N_B = \frac{\text{SEL}}{\mu_e \cdot s} \tag{2}
\]

Forces on Fibres
Kerekes and Senger (2006) estimated the normal force on a fibre, \( f_N \), to be:

\[
f_N = \frac{\sqrt{\pi \cdot d_o \cdot C_s \cdot \frac{g}{3} \cdot \sqrt{k \cdot G}}}{0.012 \cdot T} \left( \frac{\text{SEL}}{\mu_e \cdot s \cdot g \cdot z} \right) \tag{7}
\]

Assuming friction to act on fibre, we can estimate shear force on a fibre from:

\[
f_s = \mu_e \cdot f_N \tag{8}
\]

The terms in these equations are defined in the Nomenclature.

Estimations of values for parameters
Coefficient of Friction
The effective coefficient of friction is defined as normal force divided by the frictional force of resistance in the plane of the material surface subjected to force. As described earlier, the case is
more complex for bar crossings. As two bar edges approach one another and squeeze pulp into the gap between them, there is a corner force at the bar edge and a sliding friction force on the bar surface. For practical purposes, Senger and Ouellet (2002) combined the two into an “equivalent tangential coefficient of friction”, \( \mu_e \), which is the tangential (shear) shear force divided by the normal force. For mechanical pulps in high consistency refiners, they measured values in the range 0.5 to 0.8. Olender et al (2007) found a similar range of values for different stages of mechanical pulping: 0.83 for primary stage and 0.49 for reject refining. For low consistency refiners, Goncharov (1971) measured \( \mu_e \) values of 0.11. For low consistency mechanical pulp, Prairie et al (2008) found a value of 0.14. The larger values for coefficient of friction for the HC mechanical pulps are likely due to a large corner force.

**Force-Bearing Bar Length**

The variable \( z \) represents the fraction along a bar length containing load-bearing fibre that supports force. The fractional bar coverage by fibre has been measured optically. For a chip refiner, Stationwala et al (1992) found 50 to 85% of the bar surface to be covered with pulp in the form of discreet flocs. For LC refining, Hietanen and Ebeling (1990) found that for an untypically low consistency of 1.1%, that fibres covered only 10% of the bars. However, our interest in this work is in “load-bearing” not “optical” coverage, that is, the fraction of pulp that supports force.

In another approach, May et al (1988) employed measurements of axial thrust on a refiner and matched these to pulp compression data. They estimated bar coverage to be 16% and 5% respectively for the primary and secondary stage atmospheric refiners.

Lundin et al (2008) estimated bar coverage of chemical pulp in an LC refiner from loadability studies based on power, gap size, and a theoretical analysis of force in gaps. Their estimates for fractional bar coverage, \( z \), were 0.056 and 0.332 for 2 and 4 % consistency respectively.

More recently, using a force sensor of length 5 mm along a bar in an operating refiner, Olender et al. (2007) measured forces exerted by successive bar crossings in a primary and a rejects refiner in mechanical pulping. Using the same sensor, Prairie (2008) measured forces in LC refining of mechanical pulp. These authors measured bar-to-bar variability at a point on a stator bar over which rotor bars passed. They defined an “occurrence ratio” as the fraction of bar crossings that registered a force above a small threshold level. If we assume this variability to reflect the variability along a bar, we may employ the occurrence ratio to estimate \( z \). The values obtained are given in Table 1.

<table>
<thead>
<tr>
<th>Refiner</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC Primary Stage Refiner</td>
<td>0.66</td>
</tr>
<tr>
<td>HC Rejects Refiner</td>
<td>0.82</td>
</tr>
<tr>
<td>LC Mechanical Pulp Refiner</td>
<td>0.95</td>
</tr>
</tbody>
</table>

**Comparisons of predicted force to measured forces**

**Calculation of SEL**

We now compare estimates made from the above equations to measurements in refiners. First we consider methods of calculating SEL.

Refiner plates are typically characterized by a Bar Edge Length (BEL) per rotation, defined as the product of the number of bars on rotor and stator and the bar length, often specified in units km/rev. When used for a particular refiner, the BEL is multiplied by the rotational speed \( \omega \) to give the Cutting Edge Length (CEL), that is, \( CEL = BEL \omega \). The effect of bar angle \( \phi \) to the radius may be included in different ways. For example, the TAPPI (1994) definition of SEL for power \( P \) is:

\[
SEL = \frac{P \cdot \cos \phi}{CEL} \tag{9}
\]

There are other ways of accounting for bar angle. In deriving the C-Factor, Kerekes (1990) used a tangent form shown below in his C-Factor analysis. Interestingly, this gave a maximum in the number of bar crossing events at an angle of \( \phi = 26^\circ \), an angle close to ones commonly used in industrial practice. The tangent form of SEL gives:

\[
SEL = \frac{P}{CEL \cdot (1 + 2 \cdot \tan \phi)} \tag{10}
\]

More comprehensive means of calculating SEL have developed by Roux et al and are described in Roux (2001). However, for the purposes of this study, and given the assumptions and approximations made, we employ the simple forms of SEL.

**Low-Consistency Mechanical Pulp Refiner**

Fig 1 shows the normal and shear forces in a low consistency mechanical pulp refiner measured by Prairie et al (2008). They also measured the “shear work” and compared this to the SEL, using the cosine form of SEL (Eq 9). They found the SEL energy to be about 35% of the measured value. On the other hand, if the tangent form of SEL (Eq 10) had been used, the predicted value would be about
70% of the measured value. Altogether, the agreement with experiment was considered reasonably good given the likelihood that the point of measurement was not representative of the full working length of the refiner (Prairie et al., 2008).

**HC Primary Stage Mechanical Pulp Refiner**

Olender et al. (2007) measured bar forces in a high consistency (20%) mechanical pulp primary stage (chip) refiners as shown in Fig 2. This refiner had a 1.7 mm bar width and manufacturer specified \( \text{BEL} = 31 \text{ km/rev} \). The average power input was 675 kW and the rotational speed was 1900 RPM. This gave \( \text{SEL} = 0.69 \text{ J/m} \).

The measured average forces over 3 radial sections of the plate were \( N_F = 220 \text{ N/m} \) and \( F_F = 160 \text{ N/m} \). We may compare these values to ones predicted from \( \text{Eq 3} \) and \( \text{Eq 4} \) for a value of \( s \) equal to the bar width of 1.7 mm. In doing so, we obtain \( F_F = 405 \text{ N/m} \) and, from the measured coefficient of friction \( \mu_E = 0.83 \), \( N_F = 487 \text{ N/m} \). Clearly, the estimated values are larger than the measured ones, by a factor of about 2.3.

A potential explanation for the larger predicted values may lie in the fact that impacts are not exerted by individual bars, but in some cases, by a succession of bars, as is evident in Fig 2. This suggests a larger sliding distance than \( s = 1.7 \text{ mm} \). Indeed, if \( s \) were twice the bar length (3.4 mm), the predicted force would be half the above estimate, and close to the measured values. Thus, in the chip comminution stage of mechanical pulping, reduction of chips to fibre may involve a single impact spread over multiple bar crossings. Yet another explanation may be that forces in the breaker bar section, which are likely to be large, were not measured. These would have increased the average measured forces to ones closer to the predicted values. However, given the presence of chips, it is likely that the use of SEL is less suitable for primary refiners than is the case for later stages of mechanical pulping where most fibre development takes place.

**HC Mechanical Pulp Reject Refiner**

Olender et al. (2007) also measured bar forces in a reject refiner as shown in Fig 3. This refiner had a manufacturer-specified \( \text{BEL} = 75 \text{ km/rev} \) and operated at 1800 RPM. The refiner had three radial segments of differing bar widths: 2.54, 1.91, 1.4 mm. The power to the refiner was about 3000 kW, giving \( \text{SEL} = 1.33 \text{ J/m} \). The measured average peak forces were \( N_F = 1220 \text{ N/m} \) and \( F_F = 580 \text{ N/m} \).

The values of bar force predicted from \( \text{Eq 3} \) and \( \text{Eq 4} \), taking \( s = 1.9 \text{ mm} \) and the measured coefficient of friction \( \mu_E = 0.49 \), gives \( F_F = 700 \text{ N/m} \) and \( N_F = 1428 \text{ N/m} \). These predicted values are larger than the measured values, by a factor of about 1.2, which is reasonably good agreement. This agreement is better than for the case for the chip refiner, which is to be expected given the greater uniformity of this refiner evident in comparing Fig 2 and Fig 3 shown earlier. A summary of these forces is given in Table 2.
Fig 3. Measurement of normal and shear force on 5 mm bar segment in a high consistency reject refiner (Olender et al., 2007).

Table 2. Comparison of Measured and Predicted Shear Forces

<table>
<thead>
<tr>
<th>Author</th>
<th>Refiner</th>
<th>Predicted Force on Pulp (N/m)</th>
<th>Measured Force on Pulp (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olender</td>
<td>HC Primary</td>
<td>405*</td>
<td>160</td>
</tr>
<tr>
<td>Olender</td>
<td>HC Rejects</td>
<td>700</td>
<td>580</td>
</tr>
<tr>
<td>Prairie</td>
<td>LC Conflo</td>
<td>118 (cos)</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>55 (tan)</td>
<td></td>
</tr>
</tbody>
</table>

* Pulp mass spread over several bars, as suggested in Fig 2.

We may note that forces in the breaker bar section were not measured in the experimental work.

Pressure on Fibre Mass

Having estimated the average force per bar length, we now consider the pressure exerted by this force on fibrous material. This is accomplished using Eq 5 and Eq 6. For $z$, we employ the occurrence ratio as discussed earlier. We assume $b$ to be equal the bar width. The estimated pressures are shown in Table 3.

Table 3. Estimated Pressure on Fibre in Refiner Gaps.

<table>
<thead>
<tr>
<th>Refiner</th>
<th>$SEL$ (J/m)</th>
<th>$b$, $s$, $z$</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC Primary</td>
<td>0.69</td>
<td>1.70, 0.66</td>
<td>0.20</td>
</tr>
<tr>
<td>HC Rejects</td>
<td>1.33</td>
<td>1.90, 0.82</td>
<td>0.78</td>
</tr>
<tr>
<td>LC Conflo</td>
<td>0.45</td>
<td>2.54, 0.95</td>
<td>0.16</td>
</tr>
</tbody>
</table>

We may compare the above pressures to ones reported in the literature. For a primary mill-scale TMP refiner, Eriksen et al. (2005a, b) reported average pressure of 2.5 MPa, which is about an order of magnitude larger than that for the primary refiner in Table 3. Senger et al. (2004) reported pressure peaks up to 4 MPa in a lab high consistency refiner, noting that these occurred in the initial part of the impact at a bar crossing. For an atmospheric disc pilot refiner, Eriksen et al. (2005b) found pressure peaks up to 6 MPa and average pressures in the range 0.2-0.45 MPa. The latter values are about the levels shown in Table 3. These considerable differences in measured pressure are likely due to the extreme heterogeneity of fibre in distribution in primary stage refining. These factors are accounted for in $b$, $z$, and $s$ but are largely unknown. For example, the finding of Senger that the large pressure occurs in the initial part of the impact suggests small values of $b$ and $s$. Clearly, values of $b$, $z$, $s$ must be better known for better comparisons.

Goncharov (1971) measured pressures on bar surfaces during bar crossings for low consistency refining of a mechanical pulp. He found the peak pressure to be approximately 3.4 MPa over the surface of the bar near the leading edge of a bar at an $SEL = 1.5$ J/m. From Eq 5 this peak pressure would correspond to an average pressure of 1.7 MPa. If we assume $s = b = 3$ mm and $z = 1$, Eq 5 predicts an average pressure of 1.6 MPa, which is in close agreement with the measured value.

Comparisons of Forces on Fibres

There are few sources of data for forces comparing force on fibres. Indeed, forces on fibres within flocs vary considerably. Batchelor and Ouellet (1997) showed that force on a fibre in a floc could vary from 0 to 0.2 N simply as a result of fibre orientation with respect to the bar edge. Kerekes and Senger (2006) estimate forces on fibres using Eq 7 and found an approximate force $f_5 = 0.17$ N for $SEL = 2$ J/m. This gives $f_s = 0.034$ N. In recent work, using a different approach, Lundin et al. (2008) predicted $f_5 = 0.47$ N. These values are reasonable given that the tensile strength of a softwood chemical pulp fibre is about 0.1N.

Recognizing that predictions of forces on individual fibres can only be very approximate, we may realistically only employ Eq 7 and Eq 8 to predict trends. A strong trend observed in low consistency refining of chemical pulps is fibre shortening for decreasing gap size. As shown in Fig 4 and Fig 5, there is a sharp decrease in fibre length at a critical gap size. It is reasonable to conclude that this critical gap size occurs when force on fibres equal or exceed the rupture strength of fibres.

Fig 4. As gap size decreases for a given $SEL$, fibre length decreases dramatically at a critical gap size (Lundin, 2008). The consistencies from left to right at 2.3 mm fibre length are: 3.0, 4.0, 6.0, and 5.0%. No explanation is available for the single low value at 0.3 mm for 6.0%.
Fig 5. Decreasing gap size to a critical level causes an abrupt decrease in fibre length (Mohlin, 2006).

Lundin (2008) measured the influence of gap size on fibre length for differing consistencies when SEL and other factors remain constant. His data are shown in Fig 4. These data show a sharp decrease in fibre length occurring at a nearly constant ratio of consistency to gap size, $C_s / T$, specifically at values of 16, 17, 23, 18 for the 4 cases tested. Eq 7 predicts a constant force for this constant ratio under the conditions of these tests.

Lastly, it should be noted that gap size controls power in an operating refiner. Thus, as shown in Eq 7, a change in gap size changes forces on fibres by two separate means, through SEL and T. Both act in the same direction, for example, they give larger force for smaller gap size. The direct effect of $T$ is stronger given the 0.7 power of SEL. This likely accounts for the strong influence of gap size in low consistency refining observed by Mohlin (2006).

The strong effect of gap size also likely accounts for the observations of Murton et al (2002) in high consistency mechanical pulping. They found that “refining intensity determined from energy and measured residence times did not correlate well with pulp quality. In contrast, the refiner plate gap correlated well with pulp quality”.

**Summary and Conclusions**

This study has addressed the question of estimating forces in refiners and verifying predicted forces by experimental measurement. Predictions of forces on bars and fibre mass were shown to compare favourably with experimental measurements for both high consistency and low consistency refiners for mechanical pulp. The equations for force on individual fibres showed trends observed in experiment, demonstrating the strong influence of gap size and Specific Edge Load on fibre shortening. In summary, it appears possible to estimate forces by relatively simple means and thereby employ forces rather than energy as a suitable basis for refining intensity.

**Nomenclature**

- $b$: Bar width covered by load-bearing fibre, m
- $C$: Pulp consistency, fraction
- $d_o$: Outer diameter of fibres, m
- $G$: Groove width, m
- $k$: Fraction of groove width from which fibre captured
- $l$: Fibre length, m
- $s$: Distance of bar movement over which force is exerted, m
- $T$: Gap size, m
- $z$: Fraction of bar length covered by fibre, dimensionless
- $\mu_E$: Effective coefficient of friction

**Literature**
