A method to estimate fiber trapping in low-consistency refining

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ABSTRACT: Softwood kraft pulps at consistencies from 1% to 6% were refined in a conical laboratory refiner. For each consistency, the refiner power was measured as a function of the gap between the rotor and stator. The data were analyzed for no-load power, and the net refining power was fitted with a negative exponential function. The fitted functions for no-load and net-refining power were then used to estimate the gap at which the fibers first take up load. The number of fibers trapped was assumed to be proportional to this gap. The value of this gap was used to convert the measured gaps into fiber mat strains, or the strains of compression for the fiber mats. The net refining power versus fiber strain was a direct function of the pulp consistency. This finding indicates that the fraction of the refiner bars that trap fibers is proportional to the pulp consistency. A reduction in bar coverage during lower fiber trapping increased the harshness of the refining on the fibers.

Application: Refining efficiency can be considered in terms of how fiber mat trapping is affected by changes in pulp consistency, the degree of refining, the average fiber length, the peripheral speed, and the bar edge wear.

Kraft pulp refining plays a major role in determining pulp and paper properties. The most important effects of refining, both beneficial and deleterious, include [1]:

- Release of secondary fines
- External fibrillation
- Curling, straightening, or shortening of fibers
- Internal delamination of wall structures
- Introducing or removing defects.

A refiner induces these changes in fiber structure by applying forces to fiber mats trapped between the rotor and stator bar surfaces. The fiber trapping process can be characterized by two parameters: (a) the fraction of the leading bar edge that traps fibers and (b) the thickness of the mat of fibers that is trapped. None of the existing methods of characterizing refiner action take either of these parameters into account.

Our purpose in this research was to develop a method by which relative changes in fiber trapping could be estimated as refining conditions change. In other words, the technique should describe and quantify the action of adjacent refiner bars on the pulp fibers with respect to changes in pulp consistency, the degree of refining, the average fiber length, the peripheral speed, or the bar edge wear.

BACKGROUND

The idea that refiners treat fibers severally rather than individually makes sense when we consider that the typical gap size between rotor and stator is 0.1-0.2 mm. This gap is several times the thickness of an individual fiber. Evidence that refiners apply force to fibers as mats comes from direct observations in the refining zone [2,3].

Three separate forces have been identified as being imposed by refiner bars on fiber flocs [4-6]. A normal force compresses the flocs, a shear force generated by the bar surface moves over the compressed mat of fibers, and a corner force is exerted at the edges of the bars. The corner force applies a tensile load to the fibers in contact with the bar edge, which is believed to be where fibers are fractured in the refining process [7]. The action of a refiner should therefore be characterized by the number of times a fiber is trapped as it passes through the refiner and by the forces applied to the fiber during each trapping [8].

To be able to treat fibers, the rotor and stator bar edges have to trap them first and work them into the gap between their surfaces. In the specific edge load (SEL) method [9], the SEL is calculated from the average energy consumed when a unit length of rotor bar crosses over a unit length of stator bar. This factor is purely a machine parameter. The method does not account for any heterogeneity of that energy distribution along the bar edge length, even though refining energy can only be transferred where a fiber mat is present between the rotor and stator bar surfaces.

The same criticism can also be made of modifications to the SEL theory, such as the modified edge load [10], specific surface load [11], and modified specific surface load theories [12]. The C-factor theory [13] takes the trapping of fibers into account but only for an individual fiber, and the probability of trapping the single fiber is described only in terms of fiber, bar, and groove dimensions.

One piece of evidence for the importance of fiber trapping is the influence that bar edge sharpness has on the refining process. Newer, sharper bars will refine the pulp fibers more efficiently [14-17]. The influence of bar edge sharpness on the refining result is not considered in any of the SEL or modified SEL methods of characterizing refiner action.

Another piece of evidence that fiber trapping is important is that refining efficiency has been observed to fall with decreasing pulp consistency [18]. This observation holds for refining with a 12-in. disk refiner, but the efficiency is unaffected by consistency when refining is carried out in an Escher-Wyss conical laboratory refiner [7]. Therefore, the reduction in efficiency with reduced consistency is likely to arise from a reduction in the trapping of the fibers.

THEORY

There are two factors that should characterize the action of the refiner in trapping and treating fibers. These parameters are diagrammed in Fig. 1. One factor is the fraction of the bar that traps fibers, which we represent as f and which is defined in Eq. 1:

$$f = \frac{\sum l_f}{\sum l_f + l_b} \tag{1}$$

where l_b is the length of the bar and l_f is the length of the fraction of the bar that traps fibers. The other factor is the number of fibers, g_0, that are trapped under the bar edge at each point where a fiber mat is trapped.

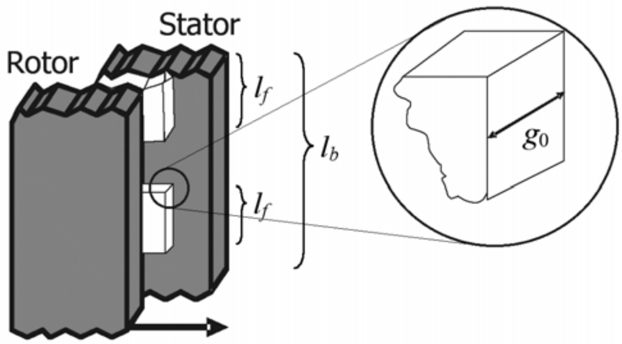
The measurements we have available in the refiner are the refiner power and the gap between rotor and stator. We cannot directly use a measurement of the gap between the rotor and stator to estimate the number of fibers that have been trapped. Instead, the gap at any given instant will depend on the total area of fibers that have been trapped (which is proportional to f), the number of fibers trapped at each point, and the thrust forcing the rotor and stator together.

Similarly, the power will depend on both the area of fibers trapped each moment and the work consumed in trapping a unit area of fibers. To use the refining power and gap measurements to estimate fiber trapping, we need a way to separate the contributions that the area of fibers trapped and the number of fibers trapped make to the measured gap and power.

The key concept behind the method presented here is that the number of fibers trapped under any segment of bar will determine the point at which the net refining power begins to rise. We call this point g_0, and it represents the point at which the fiber mat first begins to take up strain. We assume that the number of trapped fibers will be directly proportional to g_0.

The general method for determining g_0 is to fit the data with a linear no-load function:

$$P_{nl} = a + b\,g \tag{2}$$



1. Diagram of fiber trapping parameters.

The fitted function is then used for subtracting the estimated average no-load power from each data point to obtain the net refining power.

We examined several functions for fitting the data of net power and finally chose a negative exponential function:

$$P_{net} = c\,e^{-g/g_t} \tag{3}$$

This function has the advantage of being simple, and it provides a very good fit to the data. There is no theoretical basis for the negative exponential function. It was chosen because it fit the data.

Next, we need to work out a method by which g_0 can be consistently defined for each set of data. We assumed that g_0 is the point where the net power, given by Eq. 3, is 1% above the no-load power trend. This point cannot be determined from the data points, since they show scatter around the trend line. Instead g_0 was determined from the fitted functions by setting P_{net} equal to 1% P_{nl} and solving Eq. 4 numerically to find $g = g_0$:

$$c\,e^{-g/g_t} = 0.01\left(a + b\,g\right) \tag{4}$$

Once g_0 has been determined, then the data can be converted to net refining power versus the strain of compression for the fiber mat. Each data point represents the power consumed in trapping and working in fibers at the instant of measurement. To convert these data to strain, it must be assumed that the number of fibers trapped is constant and independent of the applied net power. We also have to assume that the properties of each set of trapped fibers is constant.

The final step in the analysis of each data set is to use the calculated value of g_0 to convert the measured gaps into strains:

$$\varepsilon = \left(g - g_0\right)/g_0 \tag{5}$$

I. TECHNICAL SPECIFICATIONS OF THE PROLAB™ REFINER

Power, kW	30
Rotor diameter, mm	
Minimum	58
Maximum	130
Pulp consistency, %	2-7
Pulp flow, L/min	50-120
Pulp feeding pressure, bar	0.5-6.0
Rotational speed, rpm	600-4500
Peripheral speed, m/s	
Minimum	5-14
Maximum	10-27
SRE/batch, kW·h/ton	10-45*
SEL, J/m	0.1-6.0*
SSL, J/m^2	115-1500*

*Depending on type of fillings and pulp.

This value can then be used to calculate relative changes in the bar coverage fraction, f, between refining measurements. This calculation is based on an assumption. For a given pulp at a constant value of strain, it can be assumed to a first approximation that P_{net} is proportional to f, as expressed in Eq. 6:

$$P_{net} \propto f \tag{6}$$

EXPERIMENTAL

A Prolab laboratory refiner from Metso Paper was used in the experiments. The technical specifications of the refiner are listed in Table I. The refiner was equipped with standard long medium (LM) conical fillings, with a crossing edge length of 52 m/rev, a bar width of 5 mm, a groove width of 6 mm, and a crossing angle of 18°. The refiner handles softwood slurries from 2% to 7% consistency, with a typical batch size of 50 L. The refiner was operated with the rotor revolving in the non-pumping direction. The rotor position is measured by an inductive linear position sensor from the rotor axial movement.

To determine the refining gap properly, we must locate the position where the fillings first come into contact. To determine the point of bar to bar contact, we performed a zeroing procedure while running the refiner either dry or with water at 1500 rpm. The position of bar to bar contact was determined by a specific vibration level and was stored as the zero point. The actual refiner gap was then calculated from the absolute linear position by subtracting the zero value, which accounts for the geometry of the fillings.

A limitation of this procedure is that the contact position varies from measurement to measurement, with a range of ±0.03 mm around the average. Whether the measurements were made dry or wet had no discernible effect on the zero position. All trials within the consistency series (1-6%) were performed after a single zeroing procedure, and a separate batch of pulp was prepared for each trial. The trials with unrefined pulp were performed at pulp consistencies of 1%, 2%, 3%, 4%, 5%, and 6%. For each consistency, we carried out a refiner loading sequence (2 mm, minimum, 2 mm) at the rotational speeds of 600, 1500, 2250, 3000, and 4000 rpm, corresponding to rotor peripheral speeds 4.0, 10.2, 20.4 and 27.2 m/s at the larger cone diameter. Between the loading sequences, the rotational speed was increased in steps of 100 rpm per 15 s. For comparison, a refiner loading sequence was performed with 4% pulp refined to 283 kW·h/ton at 1 J/m (LM fillings).

The softwood ECF-bleached dry lap kraft pulp used in the experiments originated from a pulp mill in southeastern Finland. The reinforcement pulp was produced in August 2003 and had a length-weighted fiber length of 2.44 mm and an average fiber coarseness of 0.183 mg/m.

RESULTS

The method presented here utilizes the data from a refiner loadability curve. In Fig. 2 an example of such a curve is shown, where the refiner net power is consumed as a function of the refining gap between the rotor and stator bars. The pulp consistency was 5%, the refiner speed was 1500 rpm, and the pulp had already been refined for 283 kW·h/ton when the measurement was made.

The data for the refiner loadability curve of power vs. gap in Fig. 2 were collected by closing the gap from 1.1 mm to 0.2 mm and measuring the refiner power. The data can be divided into two parts. From 1.1 mm to about 0.65 mm, the measured power is only the no-load power. For gaps under 0.65 mm, the measured power is the sum of no-load and net refining power, where only the net refining power is actually consumed in mechanically treating the fibers.

As the rotor and stator are forced closer together, the net power of refining is increased. This increase is not a result of increased fiber trapping. Instead, it reflects more power being required as the refiner applies more strain to the fiber network to compress the fiber mat into the smaller gap.

In this work, we assume that fiber trapping does not decrease as the gap is reduced. If trapping were to decrease, then we would expect to see the net power drop at that point, because less fiber trapping would mean less work for the refiner. None of the data we have collected at 1500 rpm shows such a drop, although a drop of this kind is occasionally observed when this refiner is operated at 600 rpm.

Fitting procedure

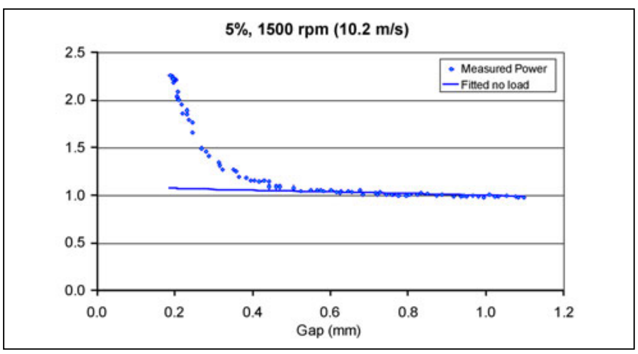
The fitting procedure is illustrated in Fig. 2 and Fig. 3. To obtain the net refining power, P_{net}, we fitted the data between 1.1 mm and 0.71 mm to a straight line according to Eq. 4 to obtain the no-load power. In this case, the no-load power, P_{nl}, was 1.095 - 0.091 g. The fitted function for P_{nl} was then used to subtract the no-load power from each data point. The fitted no-load power is shown in Fig 2. The negative exponential function for P_{net} was fitted to the data, after the no-load power had been subtracted, and is shown in Fig. 3.

The final fitted negative exponential function was

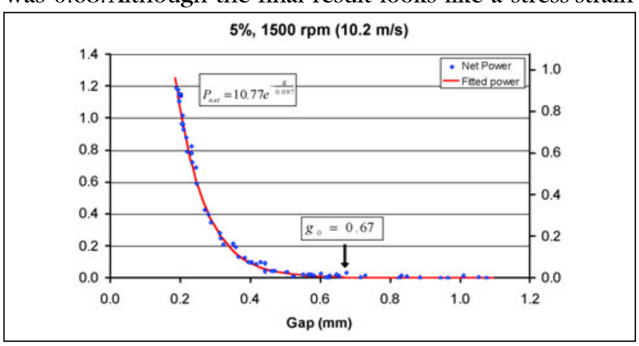
$$P_{net} = 10.77\, e^{-g/0.097} \qquad (7)$$

for this data set. The point at which the fiber mat begins to take up strain, g_0, was determined from the fitted functions by solving Eq. 4 numerically to find $g = g_0$. In the case of the data given here, the solution was 0.67 mm. This value of g_0 has been indicated in Fig. 3. The definition given in Eq. 4 appears reasonable when compared with the data. The final step in the analysis of each data set is to use the calculated value of g_0 to convert the measured gaps into strains by using Eq. 5.

The final outcome is shown in Fig. 4. The maximum compressive strain achieved at the highest level of loading was 0.68. Although the final result looks like a stress-strain



2. Refiner net power as function of bar clearance at 5% consistency for 1500 rpm and for pulp that had been refined to 283 kW·h/ton. The solid line indicates the linear trend fitted to the no-load power.



3. Net refining power vs. gap for a 5% consistency suspension of ECF pulp running the long medium fillings at 1500 rpm.

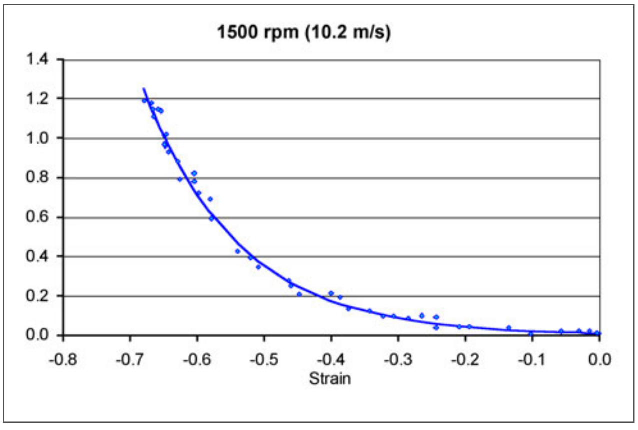
curve, it is not directly comparable to the stress-strain curve that would be obtained by testing a single uniform sample. The strain imposed on a mat of fibers that are trapped and refined will increase from 0 to the maximum negative strain and will then decrease during each bar crossing.

The measured power will be an average of power consumed at all points in the refining zone, including the points where the fiber mat is being loaded or unloaded or where no refining takes place, either because a fiber mat was not trapped or because two bar surfaces are not present. Each point also represents the refining of a different set of fibers each time, and it is implicitly assumed that these sets of fibers are representative of the pulp as a whole.

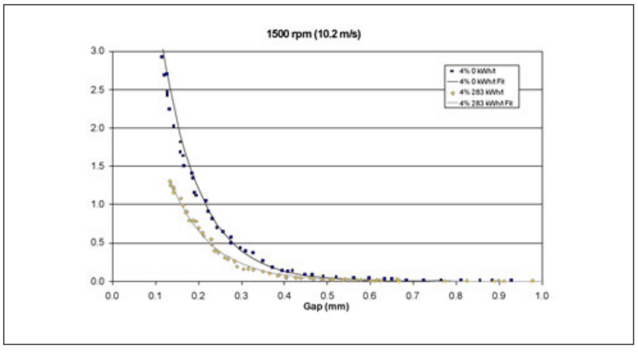
Loadability curves

To compare loadability curves obtained under different refining conditions, it is important that the state of the fibers be the same, because the compression characteristics of a mat of fibers changes during the refining process. The refiner loading curves for unrefined stock and for stock that had been refined to 283 kW·h/ton are shown in Fig. 5.

The power required to run the refiner at a given gap was considerably less for the refined fibers. This difference is not likely to be arising from any change in fiber trapping. Instead the drop in required power arises because refined fibers are more flexible and collapsed than unrefined fibers.



4. Net refining power as a function of compressive strain level for refining a 5% consistency suspension of the ECF pulp at 1500 rpm.



5. Refiner loading measurements made at 4% consistency and 1500 rpm using unrefined pulp and pulp refined to 283 kW·h/ton.

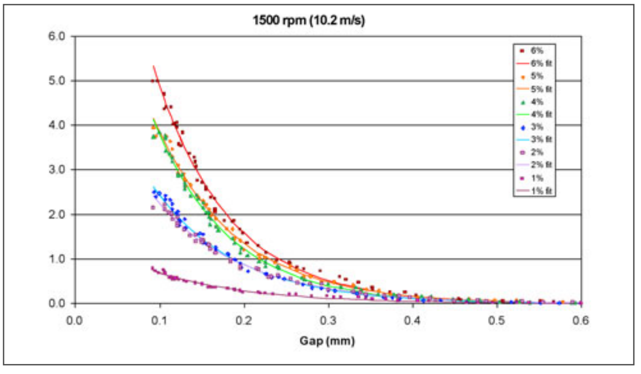
As a result, less force (and less energy) will be required to compress a mat of refined fibers to a given level of strain than required for a corresponding mat of unrefined fibers. Another factor behind the difference is that refining the pulp to 283 kW·h/ton raised the temperature of the stock from around 20°C to 60°C, which would have reduced the viscosity of the water from 1.0 to 0.4 mPa·s, making it easier to remove from the fiber network as it is compressed.

The loadability curves, as well as their fits, for the unrefined pulp at different consistencies are shown in Fig. 6. The negative exponential data fits the data well for all consistencies. The general trend with the curves is for loadability to fall as the consistency is decreased. However, at 1500 rpm the trend is not smooth because the 5% and 4% consistency curves are almost coincident, as are the curves for 3% and 2% consistency.

Consistency effects

In Table II the fitting parameters and the values of g_0 for the fits to the different consistency data are listed. Surprisingly, the values of g_0 in the table do not show large changes as the consistency falls. Indeed, the second lowest consistency of 2% has the highest calculated value of g_0. If g_0 does not vary much with consistency, then the bar edges probably have an intrinsic trapping capacity. In other words, each section of bar edge can only trap a certain fixed number of fibers under it. The consistency needs to be only high enough to provide these fibers when the rotor bar edge crosses over the stator groove. (The data in Table II indicate that the error in determining an individual value of g_0 is about ±0.03 mm for the data presented here. This error will depend strongly on the quality of the data and on how well the negative exponential model fits the data.)

From strain calculations, we saw that the refiner net power, at a given level of strain, was proportional to pulp consistency and fell as consistency was reduced. When the data collected at 1% and 6% consistency are compared, it can be seen that the net power required to refine to a given level of strain for the 1% consistency pulp is only around 1/6th of that required when refining the same pulp at 6% consistency. As the value of g_0 is approximately the same in both cases (0.60 mm at 1% and 0.64 mm at 6%), the fraction of the bar edge trapping fibers when refining at 1% consistency is also only 1/6th of the fraction when refining at 6% consistency. Therefore, the reduction in consistency greatly reduces the efficiency at which the refiner bar edges trap fibers.

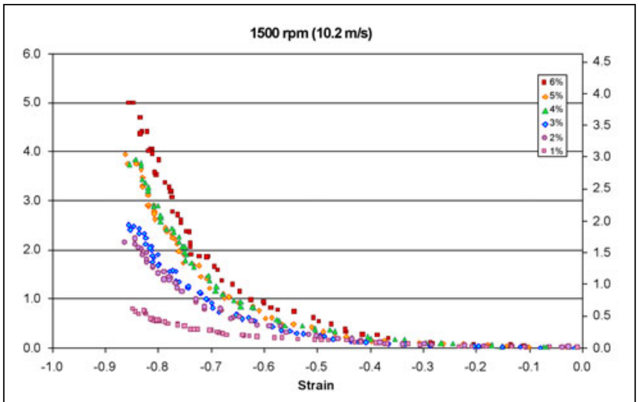


6. Refiner loadability trials of unrefined pulp for refining at 1500 rpm and consistencies ranging from 1-6%.

II. PARAMETERS DETERMINED FROM FITS OF THE DATA OBTAINED AT 1500 RPM AND DIFFERENT CONSISTENCIES

Cons., %	a*	b*	c**	g_t**	g_0, mm
1	0.224	-0.004	1.63	0.1159	0.60
2	0.964	-0.031	5.72	0.1062	0.68
3	0.954	-0.068	6.70	0.0985	0.65
4	0.997	-0.070	11.53	0.0895	0.64
5	1.052	-0.057	10.77	0.0968	0.67
6	1.236	-0.080	14.91	0.0893	0.64

*From Eq. 2. **From Eq. 3.



7. Data in Fig. 6 converted to strain using the values of g_0 in Table II.

Practical implications

Refiners are usually controlled to a set value of the specific edge load, which is directly proportional to the net power, provided that the refiner speed is not altered and the fillings are not changed. As seen in Fig. 7, the level of fiber strain required to reach a given level of net power or SEL increases as the consistency decreases, as a result of the reduction in the fraction of the bars trapping the fibers.

The harshness of the treatment applied to the fibers will be related to the strain, so decreasing the consistency while refining at constant SEL will produce a harsher treatment of the fibers. Comparison of applied SEL levels indicate that the applied fiber mat strain at 1% consistency at 0.5 J/m would correspond to a treatment of 3 J/m at 6% consistency. In other words, the applied refining intensity was six times greater than indicated for the pulp of 1% consistency.

CONCLUSIONS

To refine fibers, it is necessary to trap them between the rotor and stator bar edges and work them into the gap between the rotor and stator bar surfaces. The two parameters that characterize the trapping process are the fraction of the rotor bar surface that traps a fiber mat and the number of fibers trapped under the bar at each point where a fiber mat is trapped.

The number of fibers trapped under the bar was assumed to be proportional to the gap at which the fibers first take up load—*ie.*, where net refining power appears. Refiner power was measured as a function of gap for a laboratory refiner. The data were analyzed to remove the no-load power, and the net refining power data were fitted with a negative exponential function. The fitted functions for no-load power and net refining power were then used to estimate the gap at which the fibers first take up load. The value of this estimated gap was used to convert the measured gaps to values of fiber mat compressive strain.

Measurements were made on an unrefined softwood kraft at consistencies ranging from 1% to 6% at a speed of 1500 rpm. The gap where the fibers first take up load was almost independent of consistency for the conditions tested here.

The net refining power versus fiber strain generally fell as the consistency decreased. When the pulp consistency was 1%, the net power, or the refining intensity (SEL), at a given level of fiber strain was only 1/6 of the value when the consistency was 6%.

Fitting loadability curves seems to be a robust way to estimate changes in fiber trapping under different refining conditions. In future work, we will use loadability fitting to examine the effect of refiner speed and bar edge sharpness on fiber trapping and consequently on refining efficiency. **TJ**

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INSIGHTS FROM THE AUTHORS

Today's technology for low consistency refining is old, and the topic has been covered by numerous researcher from several angles. Seldom has it been approached, however, from the fiber's "viewpoint," which could reveal something about the poorly understood mechanisms behind the fiber treatment taking place between the refiner bars.

Provided that the theory is applicable, our work introduces a new way of describing, measuring, or quantifying the action of adjacent refiner bars on the pulp fibers. In this research, we have put forward that the fibers are being treated as a mat trapped by the refiner bar.

We experienced initial difficulties in our experiment because of scatter in the data, but we found a mathematical solution to get around this difficulty. One surprising finding was that the thickness of the mat of trapped fibers was relatively independent of pulp consistency for the reinforcement pulp at the rotational speed we tested. However, the fraction of the bar edge that trapped fibers was proportional to the consistency.

One practical issue for mills is that they might pay more attention to controlling consistency during refining. A change in consistency will change the harshness of the fiber treatment when the nominal refining intensity (SEL) has been kept constant.

Our next step is to elucidate the effects of bar wear, crossing edge length, rotational speed, fiber length, and so forth on fiber trapping.

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