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A NEW REPRESENTATION FOR LOW CONSISTENCY REFINING DATA

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ABSTRACT

The standard method of representing refining data is to plot fibre or sheet properties as a function of refiner Specific Energy Consumption (*SEC*), for separate refining trials done at different Specific Edge Loads (*SEL*). This approach does not allow for refining outcomes to be predicted when refining at other values of *SEL* and does not allow for refining conditions to be optimised to satisfy multiple constraints. In addition, the change in fibre properties is determined by the number of impacts on a fibre and the energy used in each impact, while *SEC* is the product of number and energy of impacts. This paper describes a new representation of refining data where the two axes of the plot are *SEC*/*SEL*, which is proportional to the number of impacts, and 1/*SEL*, which is proportional to the inverse of the energy used in each impact. Data from refining trials are then plotted as lines of equal value. The paper shows how flow and power limits for a low consistency refiner are represented on such a plot. The utility of the approach

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is demonstrated with refining data of a CTMP pulp with three different refining plates and three different speeds.

Keywords: Refining intensity, Number of impacts, Graphical representation, Tensile strength, Freeness.

INTRODUCTION

It is generally accepted that the outcome of refining is determined by the number of impacts, *N*, a fibre experiences and the forces imparted in each impact. Some steps have been taken in calculating these forces, but there is still a long way to go [1]–[5].

For a given set of refining conditions, including refiner, pulp and fillings, force should be related to the energy consumed in the impact, *I* [6], [7]. *I* is then a proxy for the forces applied to the fibres. The specific energy consumption, *SEC*, is given by $SEC = NI$. Equivalent treatment in refining can be expected if *N* and *I* are the same. It can also be shown [7] that for a given refiner $I \propto SEL$ where *SEL* is the more widely applied Specific Edge Load [8], [9].

The standard method for performing laboratory or pilot plant refining trials is to refine a pulp at a given *SEL*, take samples at intervals of *SEC*, measure the fibre properties and then make handsheets and measure their properties. This procedure is then repeated for refining at other values of *SEL*. The data is typically plotted as a sheet or fibre property against *SEC*, with one curve for each value of *SEL*. A typical example of such a data set is shown in Figure 1.

The disadvantages of the standard method of representing refining data are many. It is not clear how to extrapolate between curves. It is also difficult to determine refining conditions to best optimise multiple properties at lowest energy consumption. The operating range of the refiner also cannot be directly representing on such a plot. All refiners have a limited range of flow rate through the refiner and power that can be applied by the refiner, for a given set of fillings and rotational speed, and it would be very useful if these constraints could be included on the plot. Finally, from a fundamental viewpoint, it is an additional disadvantage to plot the data against *SEC* as this is product of *N* and *I*, and it is possible to get the same value of *SEC* from different combinations of *N* and *I*.

Other representations of refining data have included plotting contours of constant property (sheet or fibre) on a graph of *E* vs. *SEL* [10], the ‘bijective’ diagrams of Joris [11] in which various combinations of *SEL*, *E* and a property are plotted on the *x* and *y* axes, with the third contour being plotted as contours of equal values or the work of Croney *et al.* where a property vs. refining intensity was plotted at contours of constant *E* [12]. None of these methods satisfy all of the problems, described above, with the standard method of representing refining data.

NEW METHOD OF REPRESENTING REFINING DATA

An example of the standard method of representing refining data is shown in Figure 1. The data set was obtained from refining in a laboratory Escher-Wyss refiner. For this data set, there is very little difference between tensile strength development with *SEL*.

If we wish to plot multiple fibre and sheet properties on the same graph then it is necessary to have refiner variables on the two axes and then plot lines of equal property development. For this new representation, we propose that the two relevant variables on the x and y axes should be *N* and *I*, since these are the independent variables.

One method of calculating *N* and *I* would be to use the C-factor [6]. However, this method is not in widespread use and so it is more accessible to use the widely available refining parameters of *SEC* and *SEL*. However, as previously stated, for a given refiner and fillings, $I \propto SEL$. Therefore, for a given refiner and fillings, $N \propto SEC / SEL$. Thus, a plot of *SEL* vs. *SEC*/*SEL* will be a plot in which the axes are

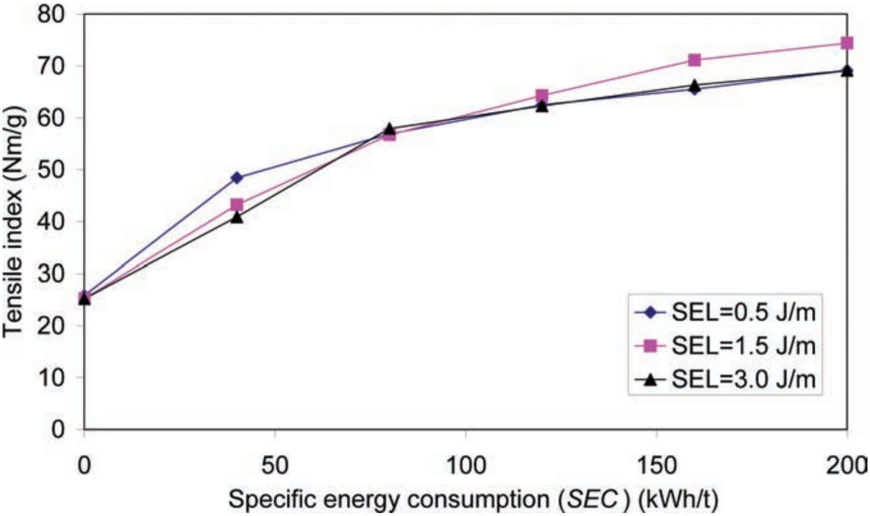

Figure 1. Typical representation of refining data. In this case, tensile index as a function of *SEC* for three different values of *SEL*.

proportional to *I* and N. It is possible to plot either quantity on the x-axis. In the work that follows we have chosen to use *SEC*/*SEL* on the x-axis.

If we use the data in Figure 1 as an example, then from linear interpolation between the data points, the *SEC* required to reach a tensile index of 60 Nm/g are 102.0, 97.2 and 99.0 kWh/t for refining at *SEL*s of 0.5, 1.5 and 3.0 J/m, respectively. These numbers will depend slightly on the method chosen to fit the data.

Figure 2 shows a plot of *SEL* vs. *SEC*/*SEL* with the three values for refining to 60Nm/kg. Each of the lines is a constant value of *SEC*, expressed in kWh/t. *SEL* is commonly expressed in J/m and so *SEC*/*SEL* is given here with the values scaled by dividing by 3.6×10^6, as this is the factor to convert kWh to Joules. The resultant numbers on the x-axis are therefore the result of dividing the *SEC*, expressed in kWh/t by the *SEL* expressed in J/m.

The problem with this representation is that lines of constant *SEC* are curved, which makes working with the data difficult and demands careful interpolation between the data points. For this data set of tensile index, all the points lie on or near the line for 100 kWh/t. Using a straight line between the points would then suggest that at a *SEL* of 1.0 Ws/m, nearly 140 kWh/t would be required to reach a tensile index of 60 Nm/g, which completely contradicts the data. This problem could be reduced by increasing the number of points measured or by a non-linear

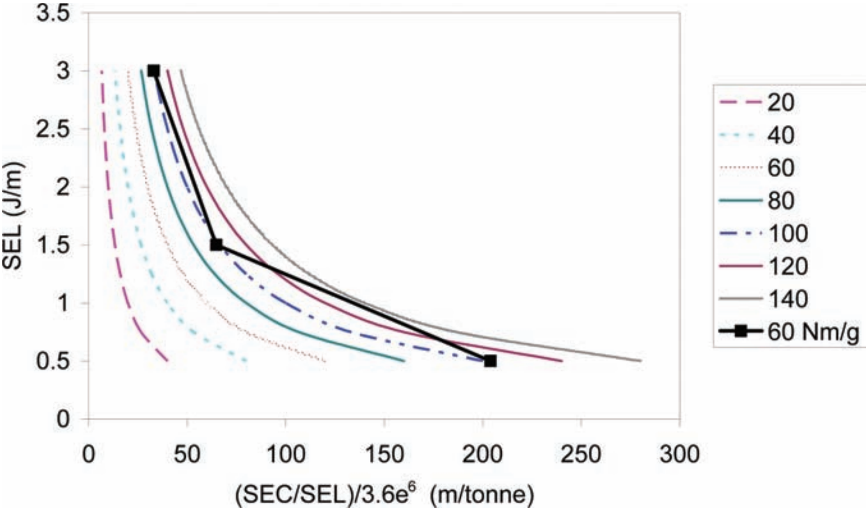

Figure 2. *SEL* versus *SEC*/*SEL* with lines of constant *SEC* (given in kWh/t), and the refining conditions required to reach a tensile index of 60 Nm/g.

fit to the data, but it nonetheless remains an issue with this method of representing the data.

However, this problem is overcome if instead of plotting *SEL* we plot 1/*SEL* on the y-axis. This is shown in Figure 3.

Lines of constant *SEC* are now linear. As in Figure 2, the three points for a tensile index of 60 Nm/g all lie around the line of 100 kWh/t. However, because the lines of constant *SEC* are now linear, a straight line fit between the data points will give the correct result that a *SEC* of 100 kWh/t is required to achieve a tensile index of 60 Nm/g, independent of the *SEL* applied. Thus this representation of refining data correctly represents what may be thought of as the 'default' outcome of refining, where the results are largely independent of the *SEL* applied for a particular range.

REPRESENTATION OF COMMON REFINING OPERATIONS AND LIMITS

Each refiner has an operating range. In order for this representation of refining data to be useful, these operating limits must also be included.

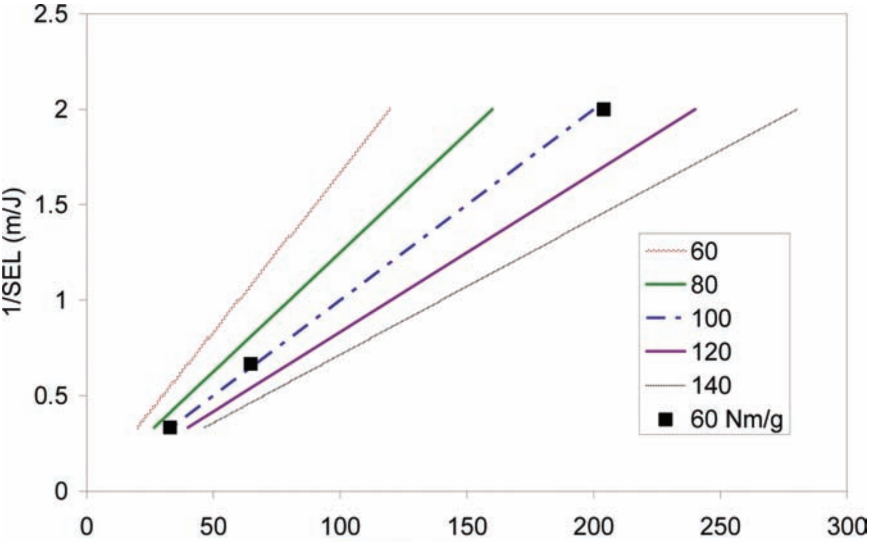

Figure 3. 1/*SEL* vs. *SEC*/*SEL* with lines of constant *SEC*.

By definition, the *SEC* is given by Eq. 1:

$$SEC = \frac{tP_{net}}{C_F V} \qquad \text{[closed loop/batch refining]}$$

$$= \frac{P_{net}}{C_F Q_{net}} \qquad \text{[continuous flow refining]} \qquad (1)$$

where P_{net} is the net power applied by the refiner to the pulp (W), and C_F is the consistency of the suspension (kg/m3). For closed-loop/batch refining, V is the total volume in the closed loop system (including volume inside the refiner and volume inside the recirculation loop) and the total refining time is t. For continuous flow refining, Q_{net} is the net volumetric flow rate through the refiner (m^3). If a continuous flow refiner is running with partial flow recirculation with recirculation ratio, r, then the actual flow through the refiner, Q_r is related to Q_{net} by $Q_{net} = Q_r(1 - r)$. *SEC* under this definition has units of J/kg, although for convenience, data is usually given in kWh/t.

The definition of *SEL* is

$$SEL = \frac{P_{net}}{\omega CEL} \text{ or } \frac{1}{SEL} = \frac{\omega CEL}{P_{net}} \qquad (2)$$

where *CEL* is the cutting edge length per revolution, projected in the radial direction, and ω is the rotational speed in revolutions/s. *SEL* has units of J/m

Therefore

$$\frac{SEC}{SEL} = \frac{t\omega CEL}{C_F V} \qquad \text{[closed loop/batch refining]}$$

$$= \frac{\omega CEL}{C_F Q_{net}} \qquad \text{[continuous flow refining]} \qquad (3)$$

which has units of m/kg.

Common refining operations and limits are:

1. Close or open the gap between the refining plates to increase or decrease, respectively, P_{net}. The result is 1/*SEL* changes but *SEC*/*SEL* is constant.
2. Change the refining time for batch refining. The result is *SEC*/*SEL* changes while 1/*SEL* is constant.
3. Change the flow rate for continuous flow refining. The result is *SEC*/*SEL* changes while 1/*SEL* is constant.

4. A Refiner flow limit for continuous flow refining gives a fixed value of *SEC*/*SEL*, independent of 1/*SEL*.
5. Maximum available net refiner power. A refiner power limit gives a fixed value of 1/*SEL* independent of *SEC*/*SEL*.

Figure 4 shows that both a plate gap increase as well as increase in refining time increases the *SEC* as each line cuts across higher and higher values of *SEC*.

The real power of the method lies in the power to simultaneously optimise refining conditions to fulfil multiple paper property requirements.

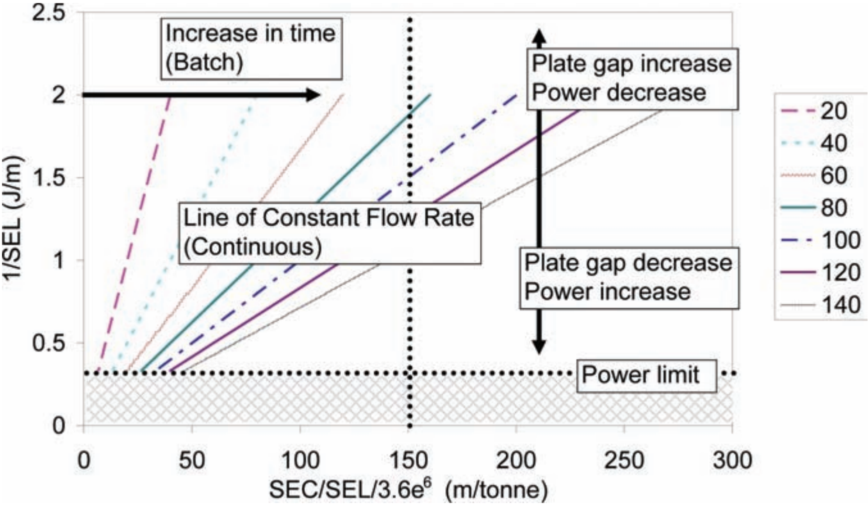

Figure 4. Common refining operations and constraints shown on a plot of *SEC*/*SEL* vs. 1/*SEL*. The legend indicates lines of different *SEC*.

METHOD APPLICATION

As an example of the application of this method of representing refining data, we have used a comprehensive data set obtained from the UBC refining pilot plant.

Experimental method

The refining experiments were done at the Pulp and Paper Centre at the University of British Columbia. The equipment consists of a flow loop with two large tanks with the capacity of 4 m^3 each, a centrifugal pump, and a single disc LC refiner with a variable speed drive with a maximum rotational speed of 1750 rpm and with a 112 kW motor.

In all experiments, softwood CTMP market pulp from Northern British Columbia (Quesnel River Pulp) was used. The supplied pulp is approximately 390 mL CSF, with a length weighted fibre length of 1.9mm. All refining trials were conducted at 3% consistency at a stock temperature of 60 °C and a flow rate of 250 lpm.

For each data point, the stock was pumped with a 40 kW pump from one tank through the LC refiner in a single pass and into a second tank. The gap was decreased over the practical ranges of plate gap achievable with a minimum of 15 samples collected per trial to provide repeatability and high resolution. The trials were run at 3 different rotational speeds of 800, 1000 and 1200 rpm for each of the plate geometries listed in Table 1. For each trial, samples were collected for refining at each gap and were measured for fibre length and freeness. Selected samples were also formed into sheets and used for tensile testing.

The plate gap was measured using an LVDT. We assume that the diameter of the pilot refiner is small enough relative to its mechanical stiffness to ensure accurate gap determination from plate position sensing. The zero-point of plate position was determined by bringing the plates together and recalibrating before each trial. Each plate was worn in using abrasive material in a stock suspension before these trials were conducted to ensure plate parallelism. The full set of data are given in [13].

Figure 5 shows the relationship between *SEL* and plate gap for the three plates.

All the results were analysed using Matlab. The analysis procedure consisted of reducing the data set, given that not all properties were measured for all points, followed by fitting a smoothing spline of the property versus *SEC* and interpolating to estimate an ISO property value. The same procedure was repeated to calculate the *SEL* associated with the ISO property value, given that *SEL* was not constant.

Table 1. Specifications of the plates used in the experiments

Plate	*Inside/ outside diameter* (mm)	*Bar width* (mm)	*Groove width* (mm)	*Groove depth* (mm)	*Bar edge length* (km/rev)	*Bar angle* (°)
1	229/406	1	2.4	4.8	5.59	15
2	229/406	1.6	3.2	4.8	2.74	15
3	229/406	3.2	4.8	4.8	0.99	15

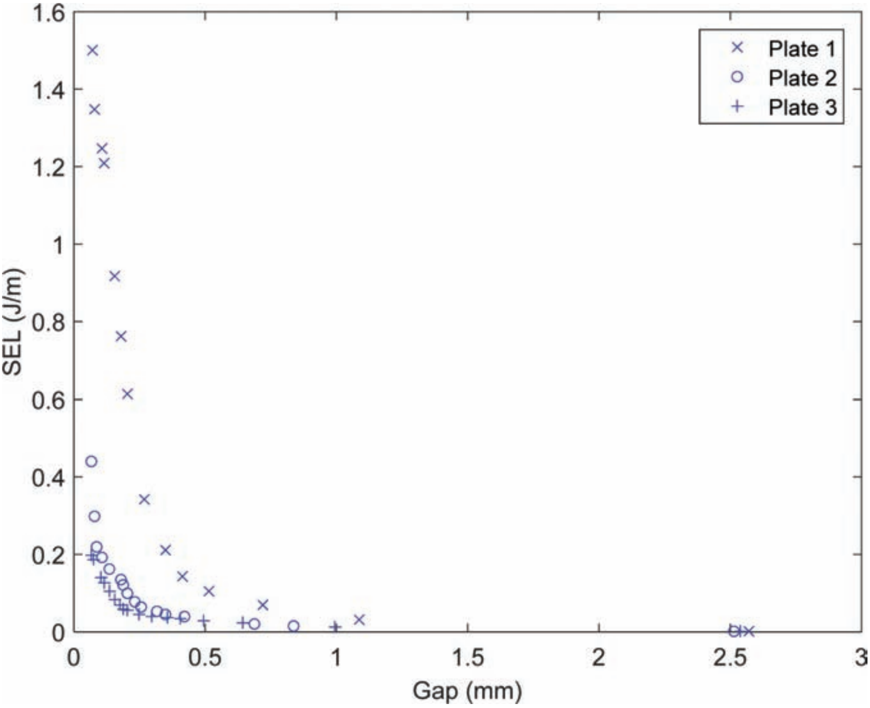

Figure 5. *SEL* versus plate at 800 rpm for the three plates.

RESULTS

Figure 6 and Figure 7 show the data for the length weighted fibre length and the freeness, respectively for the three plates running at 1200 rpm, together with the fitted smoothing splines. Clearly the fibre length is more sensitive to the plate type than the CSF, with the lowest cutting edge length plate providing a much more severe treatment.

Figure 8 then shows the ISO property data set for the 9 trials (3 plates × 3 speeds) for a freeness of 330 mL, which is an approximate drop of 60 mL and a length weighted fibre length of 1.80 mm, representing the onset of fibre cutting. While there is some scatter in the data, both sets of data are reasonably well fitted with a straight line. Using p_1 and p_2 as the fitting parameters then gives

$$\frac{1}{SEL} = p_1 \frac{SEC}{SEL} + p_2 \tag{4}$$

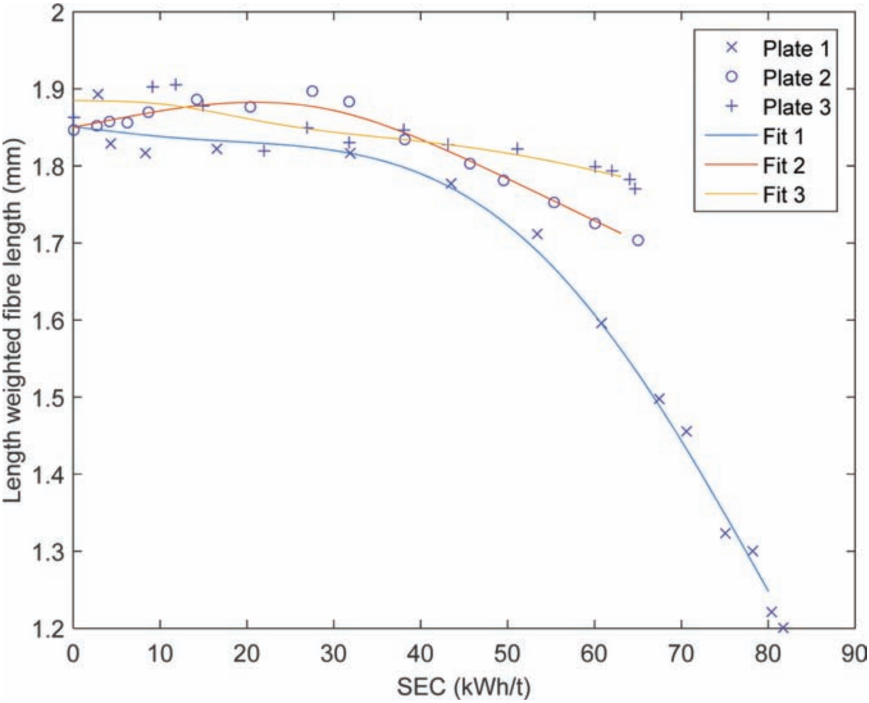

Figure 6. Length-weighted fibre length, Lw, as a function of *SEC* for the three plates at 1200 rpm.

which can be rewritten as

$$SEC = \frac{1}{p_1} - \frac{p_2}{p_1} SEL \tag{5}$$

The two terms of the fit can then be understood as $1/p_1$ is equal to the refining energy required to obtain the required fibre, suspension or sheet property in the low intensity limit, while the ratio p_2/p_1 is the sensitivity of the fibre/sheet property to changing refining intensity, with a higher value indicating a greater sensitivity. The results of the fits are given in Table 2.

Table 2. Fitting parameter results

	p_1	p_2	$1/p_1$	p_2/p_1
Lw = 1.80 mm	0.016	0.62	64.3	40.1
Free = 330 mL	0.024	0.24	41.1	9.8

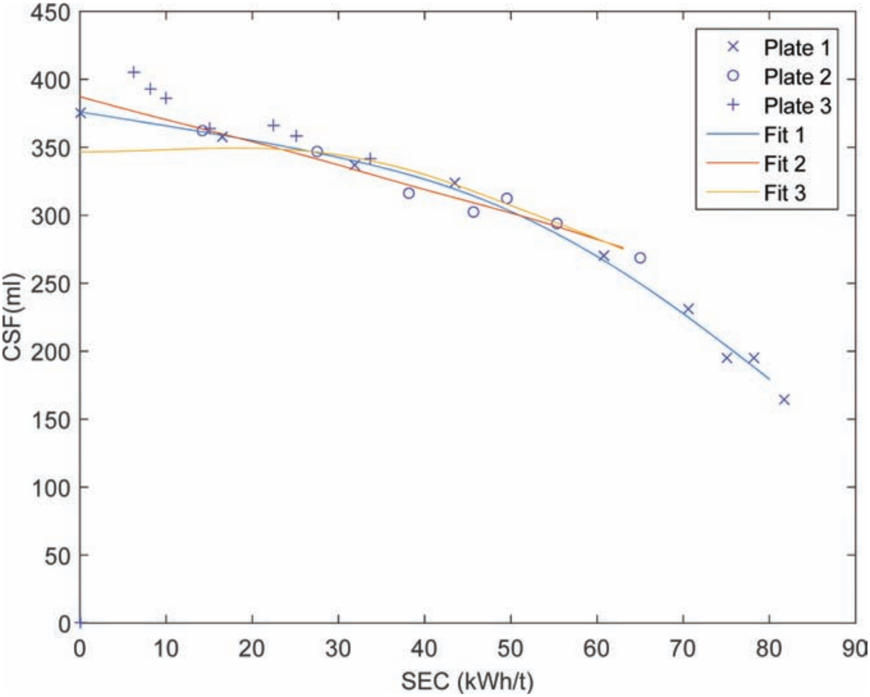

Figure 7. CSF as a function of *SEC* for the three plates at 1200 rpm.

It must be stressed that extrapolating beyond the limits of the data could give misleading results. It has been reported that softwood paper properties can fall sharply at very high values of 1/*SEL* as the refining intensity becomes too low to plastically deform the fibres [12]. In addition, very high values of *SEL* (low values of 1/*SEL*) will destroy the fibres without developing them, making any target of tensile index unattainable.

Figure 8 also shows how this method of representing the refining data can be practically applied. All of the area above the fibre length ISO property line represents data sets where the fibre length will be above 1.80 mm and so the fibres have not been cut, while all area below this line represents combinations of *SEC* and *SEL* that will produce fibre cutting. We can also see that except for the extreme left hand side, any point above the ISO freeness line will produce a pulp which simultaneously keeps freeness above 330 ml while avoiding fibre cutting.

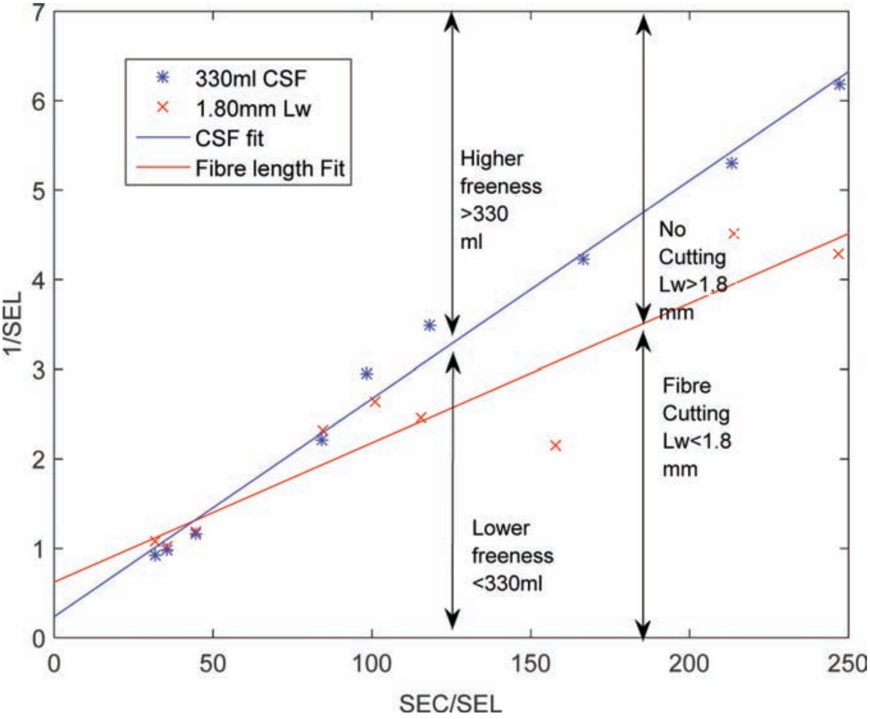

Figure 8. Interpolated data for all 9 measurement sets for a freeness of 330 ml and a length weighted fibre length of 1.8 mm.

CONCLUSIONS

A new method for representing refining data has been presented. Quantities proportional to the number of impacts (*SEC*/*SEL*) and 1 divided by the intensity of the impact (1/*SEL*) are plotted as the x and y axes, respectively. In this representation, points of constant *SEC* form straight lines. Fibre and sheet property data are plotted as lines of a constant property value. The representation offers a number of advantages of standard representations of refining data, including the ability to easily interpolate between data points and to optimise refining conditions to satisfy multiple constraints.

REFERENCES

1. R. J. Kerekes and J. J. Senger. Characterizing refining action in low-consistency refiners by forces on fibres, *J. Pulp Paper Sci.* **32**(1):1–8, 2006.

2. W. J. Batchelor, D. M. Martinez, R. J. Kerekes and D. Ouellet. Forces on Fibres in low-consistency refining – shear force, *J. Pulp Paper Sci*. **23**(1):J 40–J 45, 1997.
3. D. M. Martinez, W. J. Batchelor, R. J. Kerekes and D. Ouellet. Forces on fibres in low-consistency refining – normal force, *J. Pulp Paper Sci.* **23**(1):J 11–J 18, 1997.
4. W. J. Batchelor, T. Lundin and P. Fardim. A method to estimate fibre trapping in low consistency refining, *TAPPI J.* **5**(8):31–36, 2006.
5. T. Lundin, W. J. Batchelor and P. Fardim. Fibre trapping in low consistency refining: New parameters to describe the refining process, *TAPPI J.* **7**(7):31–36, 2008.
6. R. J. Kerekes. Characterization of pulp refiners by a C-factor, *Nordic Pulp Paper Res. J.* **5**(1):3–8, 1990.
7. R. J. Kerekes, D. Ouellet and M. Martinez. ‘New perspectives on refining intensity,’ in *3rd International Refining Conference*, pp. 1–23, Atlanta: PIRA International, 1995.
8. W. Brecht. A method for the comparative evaluation of bar-equipped beating devices. *TAPPI J.* **50**(8):40A–44A, 1967.
9. W. Brecht and W. Siewert. Zur Theoretisch/Technischen Beurteilung Des Mahlprozesses Moderner Mahlmaschinen, *Das Papier* **20**(1):4–14, 1966.
10. J. E. Levlin. Oppportunities for energy savings in low-consistency refining, *Investigacion y Téchnica del Papel* **98**:799–817, 1988.
11. G. Joris. ‘Optimization of industrial refining unit through fibrologic 4.0,’ in *Proceedings 4th International Refining Conference*, Paper 17, Fiuggi, Italy: PIRA International, Leatherhead, UK, 1997.
12. C. Croney, D. Ouellet and R. J. Kerekes. ‘Characterizing Refining intensity for tensile strength development,’ in *Scientific and Technical Advances in Refining (5th International Conference on Refining*), *Vienna*. PIRA International, Leatherhead, UK, 1999.
13. A. Elahimehr. *Low Consistency Refining of Mechanical Pulp: The Relationship between Plate Pattern, Operational Variables and Pulp Properties*, University of British Columbia, 2014.

Transcription of Discussion

A NEW REPRESENTATION FOR LOW CONSISTENCY REFINING DATA

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Bill Sampson University of Manchester

Warren, I might be missing something. If you plot one over Specific Edge Load against Specific Energy Consumption on Specific Edge Load, isn't the gradient the Specific Energy Consumption? Shouldn't all these pass through the origin?

Warren Batchelor Monash University

I am plotting one over Specific Edge Load versus Specific Energy Consumption on Specific Edge Load.

Bill Sampson

Maybe you could put a graph up? You show 1/SEL versus 1/SEL multiplied by the Specific Energy Consumption, so the gradient is just the Specific Energy Consumption, isn't it?

Warren Batchelor

Yes. One over the gradient is the Specific Energy Consumption in the low intensity limit, while the ratio of the Y axis intercept to the slope gives the sensitivity to refining intensity.

Bill Sampson

So, if I take the horizontal axis, I can get a value of zero either by having Specific Energy Consumption equal to zero, or Specific Edge length of infinity which transposes to what I see on the Y axis, so it must pass through zero. You will see an intercept because of experimental error, but it must pass through zero.

Warren Batchelor

It can pass through the origin if the energy to achieve a given ISO property is independent of intensity.

Thierry Mayade Ahlstrom-Munksjö Apprieu

So I agree with you it is interesting to find a new way of presenting refining results, but I think it is a bit complicated what you are showing us and many years ago, 20 years ago, I suggested another more simple way. On the X axis, you just put the Specific Edge Load and on the Y axis, the Specific Energy, so we keep two sorts of parameters, and for sure like you do you draw ISO-property. If you run a batch refining so your constant is on the X axis, because you are running usually at a constant Specific Edge Load, so vertically is what you do when you refine 0, 50, 100 kWh/t when you move vertically. Then what happens on the industrial refiner if you run it and control Constant Specific Energy? If the flow varies, double for instance, then you will double the power and so you will double the Specific Edge Load, so you move horizontally on this graph. And finally, if you keep the flow in the industrial refiner constant and you change the power, then you move on the line passing by the origin. If you want some examples of that kind of drawing, you can refer to the paper I gave at the APPITA conference in 1996 and also published some months later in the magazine.

Warren Batchelor

Yes, thank you. I think it would be interesting to compare what the two look like.

Jean-Claude Roux Grenoble INP Pagora

I have the same problem with your graph as Bill Sampson. If you plot the reciprocal of the Specific Edge Load, versus the ratio Specific Energy Consumption divided by Specific Edge Load. You will get straight lines passing through origins with a slope which is equal to one divided by Specific Energy Consumption, so I am wondering why you can say that it does not pass though origin. Does it mean that you calculate SEL and the ratio Specific Energy Consumption divided by Specific Edge Load differently? In that case it could explain why none are passing by zero, but I am very confused by your representation.

Warren Batchelor

Certainly, the lines of constant Specific Energy Consumption will pass through the origin. The fact that these data points are not passing through the origin is indicating that you will need different Specific Energy Consumptions to reach this property when you are changing your Specific Edge Load. So, where I have got one plate requiring a certain Specific Energy Consumption to reach for example a fibre length of 1.80 mm. Then I will change plates with a change in cutting edge length, and the Specific Energy Consumption is required to reach the same fibre length is different.