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CELLULOSE REFINING FOR FIBRE CEMENT: PART 1 (SIGNIFICANCE OF FREENESS MEASUREMENT)

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ABSTRACT

This paper determines the relationship between freeness as measured by either Canadian Standard Freeness (CSF) or Schopper-Reigler (SR) methods and the total effective refining energy. It includes the relationship of Freeness to the specific surface of the fibres. The paper arose from the author's opportunity to compare the performance of a double disc refiner with a conical refiner where each was refining the same species of unbleached Kraft pulp (P Radiata) with the same Kappa number (although in different factories). This lead to the observation that contrary to common expectation that the change in freeness of each pulp is related to input of effective refining energy to the pulp it is actually properly related to the square of the input of the effective refining energy. It was also found that the form of relationship applies to both the double disk and conical refiners.

It is demonstrated that the reason for this observation is that however measured (SR or CSF), pulp freeness is proportional to the square of the specific surface area of the pulp. Thus, it is shown that the specific surface area development of the pulp is directly proportional to the input of effective refining energy during refining.

KEYWORDS:

Cellulose refining, Significance of freeness, length distribution

INTRODUCTION

This paper is separated into 2 parts: -

In part 1 we evaluate the

a. Relationship between freeness as measured by either Canadian Standard Freeness (CSF) or Schopper-Reigler (SR) methods and the total effective refining energy. It includes the relationship of Freeness to the specific surface of the fibres and
b. Refining intensity as indicated by specific edge loading (SEL as measured in J/m) and derivation of a general equation relating freeness development with SEL and total effective refining energy

In part 2 we examine

a. Analysis of changes in fibre length, fibre width, curl and kink with changes in Freeness
b. Significance of the changes in length and freeness to the mechanical properties of fibre cement.

The paper arose from the author's opportunity to compare the performance of a double disc refiner with a conical refiner where each was refining the same species of unbleached Kraft pulp (P Radiata) with the same Kappa number (although in different factories). This lead to the observation that the change in freeness of each pulp was related to the square of the input of effective refining energy(E_{eff}^2) to the pulp and that the same form of relationship was found with both the double disk and conical refiners. [1]

One set of data was derived from an investigation of the degree of cutting of the fibre which had been refined in a double disk refiner at different intensities to varying freenesses. In this case samples of raw and refined pulp had been examined by Kajaani fibre analyser to produce complete distributions of fibre length, width, curl and kink as well as averages of these properties. In the case of the conical refiner, only information on the specific refining energy and the freeness was available along with average levels of the SEL used. Fortunately though this refiner required multiple passes through the refining set and freeness results were available after each pass so that a full refining curve could be related to the refining energy. After a substantial analysis of the data on the double disk refiner and comparison with the conical refiner, the following questions were raised,

a. Is there a universal relationship between change in freeness and E_{ff}^2 for all pulps or is this only applicable to P Radiata?
b. If the relationship is universal, what is the significance for fibre cement?

This question is answered in Part 1 of this paper because if there is no universal relationship, then we are wasting our time in further developing the relationship to include the effect of refining intensity. It will be shown in Part 1, that the relationship appears to be universal but the coefficients of the equations for CSF and SR differ and the relationship of freeness to fibre properties is derived.

We also derive a relationship to relate changes in freeness, SEL and refining energy that can be used to determine how to operate a specific refining system to achieve specific freeness and other fibre properties.

In part 2

a. we analyse the changes in fibre properties such as length, width, curl and kink with changes in freeness which we use to assess their significance to fibre cement manufacture.
b. we draw together the results of the analysis to estimate the critical length of the refined fibres and attempt to assess their significance for fibre cement.

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RELATIONSHIP BETWEEN CHANGES IN FREENESS AND EFFECTIVE ENERGY OF REFINING

Refining Cellulose Pulp

Briefly, refining cellulose pulp involves subjecting it to a crushing and grinding between fixed and moving ridged surfaces. In many ways it is analogous to "the effects of chewing on a wooden pencil" in that it has the effect of separating, splitting and disrupting the cellulose fibres so that they are softened and become malleable.

The purpose of refining in paper manufacture is to so soften the fibres so that they will lie together and bond with one another by hydrogen bonding to form a compact network that is the sheet of paper. Refining is performed for similar reasons in the production of fibre cement. Refining the fibres make them bond more readily with the cement matrix and thereby adequately reinforce it. However, in addition refined fibres are needed to provide a filter mat which is a crucial part of the manufacturing process.

There are two basic types of fibre cement –

- autoclave cured fibre cement where the cellulose fibres provide all of the reinforcing and filtration in the production process
- air cured fibre cement where the cellulose fibres provide only the filtration and synthetic fibres provide the majority of the strength.

We are concerned primarily with autoclave cured fibre cement.

Measuring the Degree of Refining of Pulp

The fibre cement industry uses freeness as measured by the standard methods of the paper industry to control the degree of refining of pulp applied in the industry. The two methods are Canadian Standard Freeness (mainly in the Anglosphere) and Schopper-Reigler Freeness (elsewhere). Both methods were developed within the paper industry to provide a means to quantify dewatering of pulp slurries during the formation of paper or board. Both methods are used to set suitable parameters to process the pulp prior to making paper and to optimise performance of the paper making machinery.

Both methods involve the filtration of 1000ml of a standard slurry of fibre and determine the overflow volume of water draining from the pulp through a screen. The CSF method measures the volume of the overflowed slurry, while the SR method measures the complement of this volume i.e. 1000ml – overflow volume. Thus SR rises in number as the pulp is refined and CSF declines. Each method uses a different concentration of fibres in the slurry and there are differences in the structure of the test equipment. Thus it is not easily possible to relate a measurement of CSF with an equivalent measurement in SR although tables of equivalence are available. Nevertheless, both methods operate by the same fundamental physical principles.

As indicated above, this paper has resulted from the observation that the freeness of the refined pulp is related to the square of the effective refining energy that is imparted to the pulp during refining. This was exemplified by the results of a comparison of refining of P Radiata pulp in two different refiner sets. On graphing SR against the Effective Refining Energy (E_{eff}), applying Excel's trendline function, trying various correlation functions to find the best fit, the chart in figure 1 was obtained. [2]

[2] It should be noted that the equations obtained when expressing E_{eff} in kW.Hr/t were more or less indistinguishable. It seems that the accuracy of Excel's trendline function is impaired when there is a large difference in the magnitude of the variables being compared. So we rescaled E_{eff} to MWhr/t.

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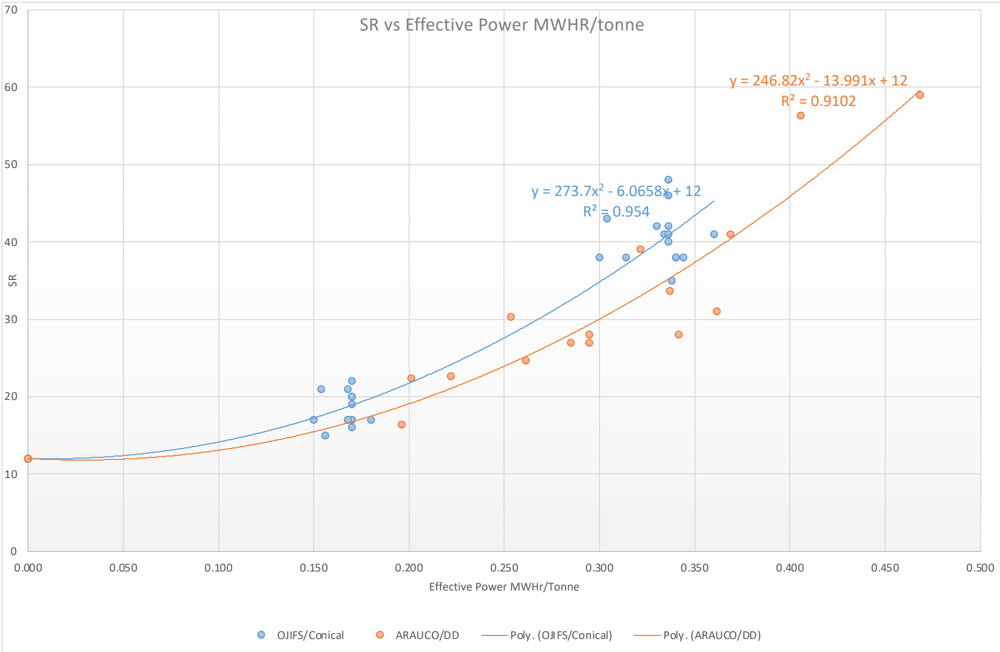


Figure 1 Freeness response of P Radiata pulp refined in 2 different refining sets

The author's expectation prior to this observation was that the change in freeness would be linearly related to the imposed E_{eff}. So while the correlation was strong and the agreement of the form of the relationship between both refining systems was compelling, this raised questions as to whether this relationship is universal or are similar relationships found with other pulps. Therefore, a number of sets of data derived from various sources were graphed, trendlines were computed using Excel and relationships similar to the above were found. Sources for the information included, brochures from various unbleached softwood pulp suppliers offering pulp for fibre cement, various investigations that the author had access to, comparison data between various pulps and detailed data on P Radiata from OJIFS. Table 1 shows the results that were obtained numerically and graphically.

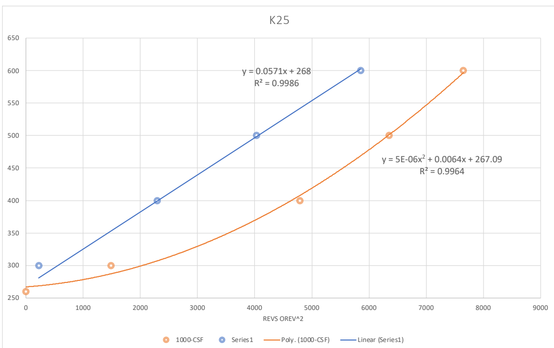
So that the freeness can be shown to rise with increasing energy and the form of the relationship was similar with SR and CSF, CSF results were displayed as 1000 – CSF or Inv CSF. This convention is followed throughout this paper whenever CSF is discussed.

Each graph shows SR or Inv CSF vs E_{eff} and E_{eff}^2. It is clear that SR or InvCSF is proportional to E_{eff}^2 for all of the softwood pulps shown irrespective of the type of pulp or refiner used. We will show below the significance of this relationship and how it should be interpreted in terms of fibre properties.not

Table 1 comparison of freenesses vs Effective Refining Energy of various softwood pulps refined

OJIFS K25

Revs	Revs^2/10^4	CSF	1000-CSF
0		740	260
1490	222.01	700	300
4790	2294.41	600	400
6350	4032.25	500	500
7650	5852.25	400	600



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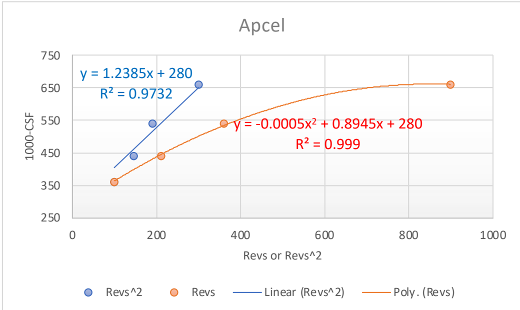
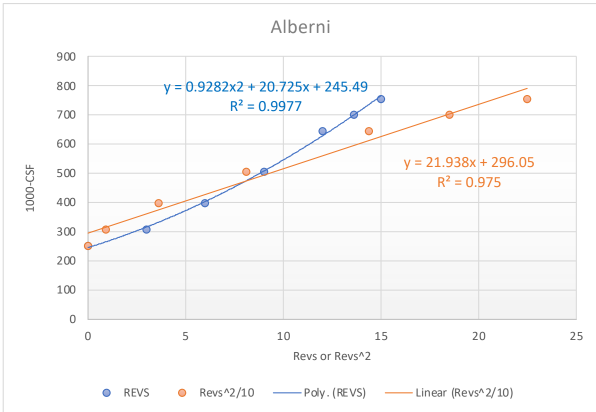
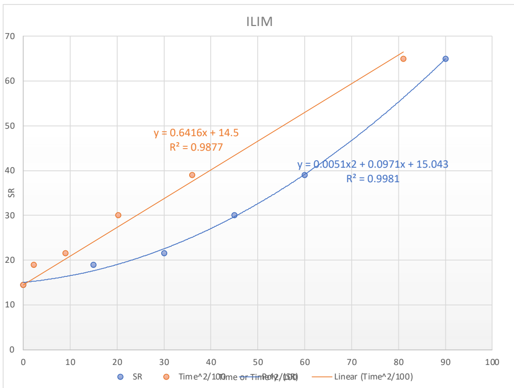
Apcel	PFI Mill		
REVS	Revs^2/100	CSF	1000-CSF
100	100	640	360
145	210.25	560	440
190	361	460	540
300	900	340	660



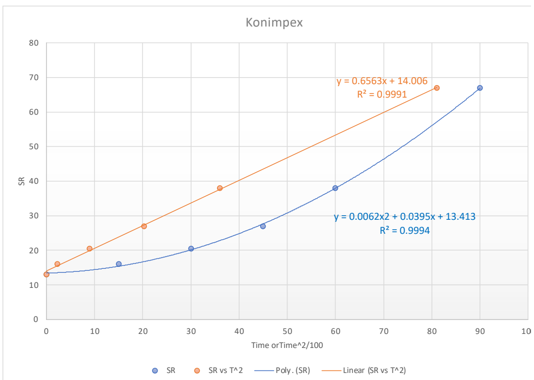
Alberni	PFI Mill		
PFI REVS	Revs^2/10	CSF	1000-CSF
0	0	748	252
3	0.9	692	308
6	3.6	602	398
9	8.1	494	506
12	14.4	355	645
13.6	18.496	300	700
15	22.5	245	755



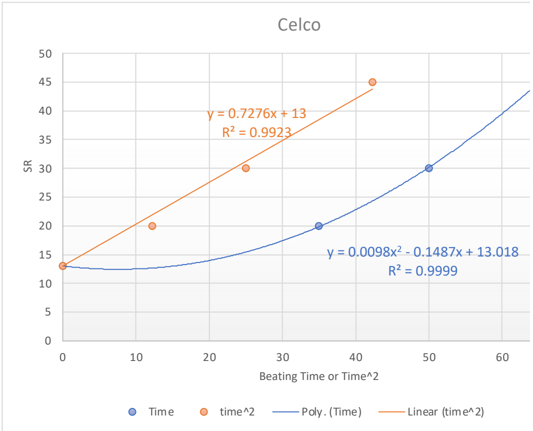
Ilim	Jokro Mill	
Time	Time^2/100	SR
0	0	14.5
15	2.25	19
30	9	21.5
45	20.25	30
60	36	39



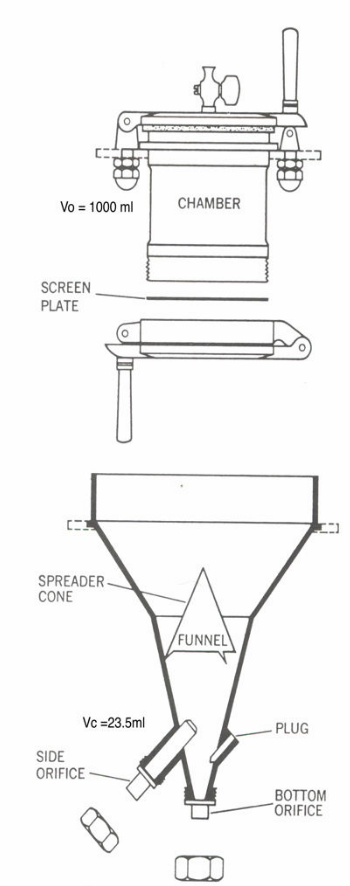
Konimpex	Jokro Mill	
Time	Time^2/100	SR
0	0	13
15	2.25	16
30	9	20.5
45	20.25	27
60	36	38
90	81	67



Celco	Valley Beater	
Time	time^2/100	SR
0	0	13
35	12.25	20
50	25	30
65	42.25	45



Significance of the Relationship between Change in Freeness and Applied Refining Energy



Canadian Standard Freeness tester.

Figure 2 CSF Tester

The relatkionship between freeness and effective refining energy devolves around what is being measured when we measure freeness. The question was answered by El-Hosseiny and Yan[i] for the Canadian Standard Freeness test. Swodzinski and Doshi[ii] simplified the analysis and extended it to the Schopper-Reigler test. Swodzinski[iii] and Boyd[iv] demonstrated that the equation (1) below was identical to the El-Hosseiny and Yan equation.

Swodzinski and Yan analysed the situation and making the following assumptions.

1. While water is discharging from the side orifice, the flow from the bottom orifice is essentially constant.
2. The resistance to flow of the screen in apparatus is insignificant compared to the resistance of the pad of fibres on the screen.

It has been found that the discharge rate of the bottom orifice does vary with the height of the water present in the cup but its effect is small in comparison with the other factors.

The resistance of the screen is several orders of magnitude less than the resistance of the pad of fibres and can therefore be ignored.

With these assumptions Swodzinski and Doshi proposed the following equation to determine the CSF

$$CSF = (V_0 - V_c) - Y \ln\left(\frac{V_0}{Y} + 1\right) \qquad 1$$

$$\text{where } Y = \frac{Q_{10}.V_0.c_0.\mu.R_f}{\rho.g.A}$$

And the variables have the following values[3]

[3] Following Swodzinski & Doshi, I am using CGS units in this part of the paper for convenience.

V_0	Volume of Test liquid	1000 ml
c_0	Concentration of fibres in the test liquid	0.3 g/litre (nominally)
V_c	Volume of cup	23.5 ml
Q_{10}	Discharge rate of the bottom orifice	Assumed constant and approximately 8.7 ml/second
μ	Viscosity of water	0.01 g/cm.sec
ρ	Density of water	1.0 g/cc
g	Acceleration due to gravity	981 cm/sec^2
R_f	Resistance of filter pad to flow of water under pressure	Unknown with units cm/g
A	Area of the screen in the apparatus	81.073 cm^2

Considering Equation 1 it is apparent that since CSF, V_0 and V_c are volumes, then Y must also have the dimension of volume. All of the components of Y are constant or measured during the CSF test with exception of R_f[4] so it is this factor that varies when CSF varies. In other words CSF is dependent on R_f.

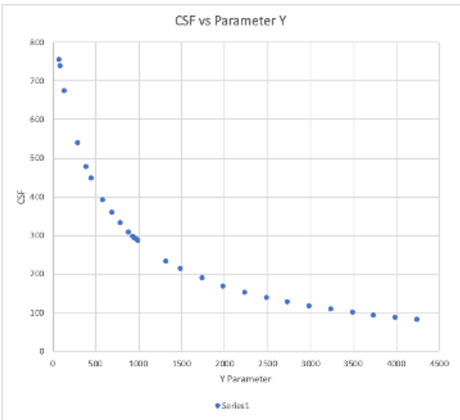


Figure 3 CSF vs Parameter Y

We can quickly check Equation 1 by varying Y from 100 to 3250 when it will be seen that CSF varies from 752 to 105 as shown in the adjoining Figure 3.

At first glance it would appear that Y should not exceed 1000 as this is the volume of test liquid. However this is not the case as it is only necessary that the dimension of Y be volume and since this is controlled by R_f, the value of Y can exceed 1000.

We need now to check if Q_{10} is actually constant and we do this using the output of the equation and results reported in Table 1[5] of Swodzinski and Doshi. We obtain the following results in Table 2 for Q_{10}

Table 2 Variation of Q_{10} with measured CSF

CSF	R_f	C_0	Q_{10}
671	4.38E+07	0.00285	9.46
445	1.38E+08	0.00303	8.66
231	3.90E+08	0.00308	8.72
113	8.26E+08	0.00322	8.88

[4] A dimensional analysis of Y confirms that R_f must have units of cm/g for Y to have dimension of Volume (i.e. length cubed).

[5] Tables 1 and 2 of Swodzinski and Doshi report R_f in units of c/g X 10^{-8}. This is technically correct as the value in their table has been divided by 10-8 so that it is more conveniently expressed as a number less than 10. So in their table a value such as 1.38E+08 is expressed as 1.38 and the values in their table need to be multiplied by 10^{+8}.

Table 2 makes clear that while Q_{10} may vary, this is very small compared to R_f and can be taken to be constant at the average of the values above (8.93 ml/sec) with only small effect on the predicted value of CSF. Indeed El-Hosseiny and Yan use a value of 8.83 ml/sec in their calculations, so the result here is consistent with them.

Interpretation of R_f and relationship to CSF

R_f has dimensions cm/g and if we multiply it by the density of cellulose (1.5 g/cm^3) we obtain a number with dimensions cm/cm^3 = cm^{-2}. Taking the square root of this number we obtain a number with dimensions cm^{-1} which is equivalent to a number that has dimension cm^2/cm^3 or the specific surface area of the fibre expressed as square centimetres per cubic centimetre (SSA_v). To convert this number to a unit of square centimetres per gram that may be more familiar to fibre cement technologists, we divide by the density of cellulose fibre. However we must first apply a correction factor that is dependent on the voidage of the filter pad of fibre. This is given by El-Hosseiny and Yan in the following equation

$$R_f = 5.55 \frac{\sigma^2 c}{(1 - \alpha c)^3} \qquad 2$$

where $\sigma = specific\ surface\ area\ of\ the\ fibre\ in\ cm^{-1}$

c = filtered pad consistency = 0.03 in cm^3/cm^3

$\alpha = bulk\ of\ the\ fibre\ in\ cm^3/g$

Assuming that the fibre bulk is 3 cm^3/g this results in the calculations of Table 3

Table 3 Calculation of Specific Surface Area by Volume and Weight

CSF	Inv CSF	R_f	bulk	c	5.5*c/(1-ac)^3	SQR(R_f)	SS
			cm^3/g	g/cm^3		cm^{-1}	cm^2/g
671	303	4.38E+07	3.00	0.03	0.22	14080	9386
445	529	1.38E+08	3.00	0.03	0.22	24990	16661
231	743	3.90E+08	3.00	0.03	0.22	42013	28000
113	861	8.26E+08	3.00	0.03	0.22	61142	40761

Graphing the estimated specific surface area of the fibre against the square root of the CSF we find a linear relationship with a strong correlation coefficient.

If we use the inverse CSF (i.e. 976.5-CSF = $Y(\ln\left(\frac{V_0}{Y} + 1\right))$ then the relation is inverted and the specific surface increases with increasing inverse CSF. A similar relationship applies to SR where the specific surface area of the fibre increases with increasing SR.

These relationships are shown in the Figure 4.

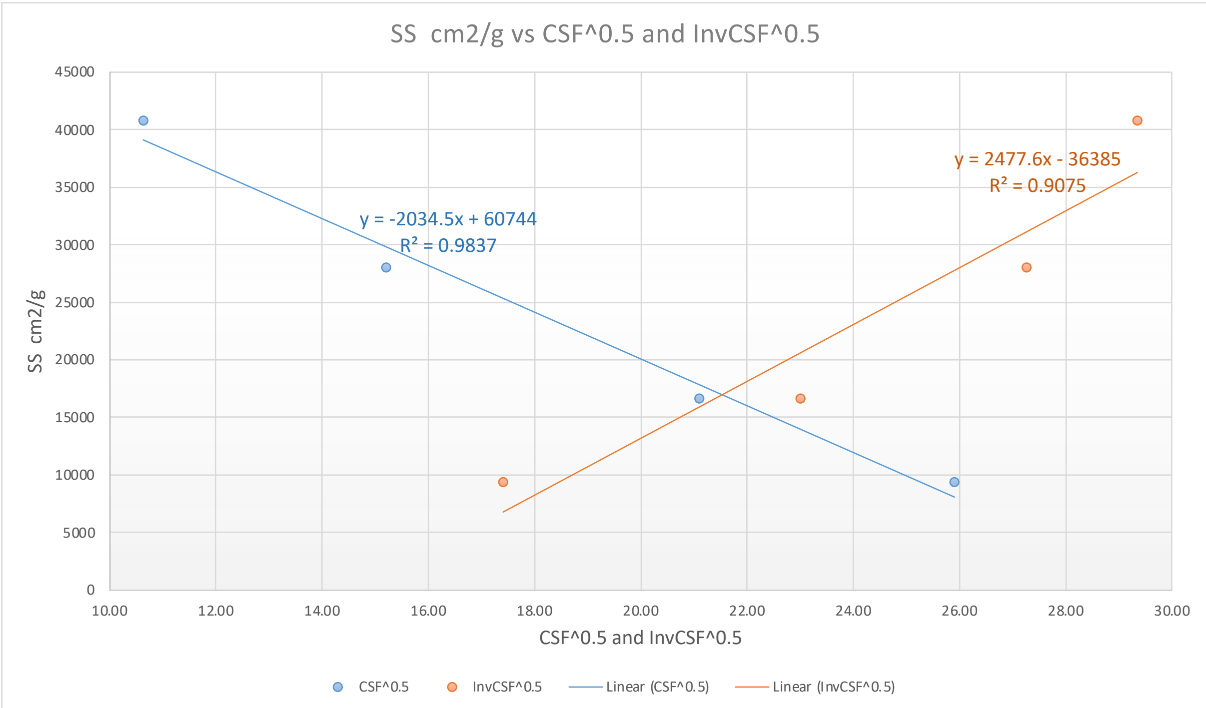


Figure 4 Specific Surface Area (cm2/g) vs SQRT (CSF) and SQRT (InvCSF)

Referring to the original question we now can see that CSF and SR are proportional to the square of the specific surface area of the fibre. Thus the relationship between SR and the square of the effective refining energy means that the change in **specific surface area of the fibre** is directly proportional to input **of effective refining energy**, which is exactly what we should expect.

Of course this does not tell us how the specific surface is generated and we need to be careful not to overinterpret this conclusion. Indeed El-Hosseiny and Yan are careful to point out that in refining for paper, specific surface area of the fibre is only important for mechanical pulps where the fibre is stiff and bonding between fibres in the paper is dependent on surface contact. They claim that for chemical pulp such as Kraft pulps the fibres are soft and compliant and that bonding is more dependent on improvements in compliancy than on specific surface area. While not stated in any of the referenced papers it is likely that cellulose for paper will be bleached and therefore softer even than in the case of mechanical newsprint pulp.

Cellulose for autoclaved fibre cement is usually unbleached Kraft pulp and while stiffer than bleached pulp because of its lignin content, the fibre is in a different environment to paper and bonding within a cement matrix will benefit from high specific surface area. There is much evidence to suggest that this is the case and will be dealt with in later parts of this paper.

DEVELOPMENT OF A RELATIONSHIP BETWEEN CHANGE IN FREENESS, EFFECTIVE ENERGY INPUT AND REFINING INTENSITY FOR P RADIATA PULP

Having established that Freeness is proportional to the square of the specific surface area of the fibres we now proceed to analyse in detail the response of the pulp to effective refining energy and refining intensity. We have 3 sets of data available for this purpose. The first was derived from a study to determine conditions under which cutting of the fibres could be limited to a specified minimum fraction of the original length[6]. [v]The second comprised data from normal operation of a conical refiner set that was operating in a factory and as noted above, the motivation for collecting this data was to compare the performance of the double disc refiner set with the

[6] This set was previously reported by the author and this paper includes a more comprehensive analysis of the results. See Cooke in the references at the end of this part.

conical refiner. The third set of data was provided by OJI Fibre Solutions and comprises a comprehensive study of the refining response of P Radiata pulp primarily aimed for manufacture of Fibre Cement. The freeness in the first two sets of data was measured by the SR method and the third set was measured by the CSF method.

It is accepted wisdom that the freeness of cellulose pulps responds linearly to refining with respect to the total specific energy input expressed as kWHr/tonne (or alternatively as MWHr/tonne as will be done here). Thus one would expect that the energy input curves would be linear in any specific system after allowing for energy losses within the refiner. We have shown above that this is not the case and it is found that the change in freeness as measured by the Schopper-Reigler method is directly proportional to the square of the effective refining energy as modified by the refining intensity. It was also shown that the same form of relationship applies when the freeness is measured by the CSF method but interpreted as the inverse or complement of CSF.

Methods

For the first two data sets the author was able to directly observe the refining of similar P Radiata pulps in separate factories that were refined in 2 different refining systems. The specific situations were as follows

Factory	Pulp	Consistency	Refining System
1	Blend of bleached and unbleached P. Radiata pulp with Kappa number between 23-25	4.2% nominal in alkaline process water	2 double disc refiners in series with controlled recirculation – circuitry shown below

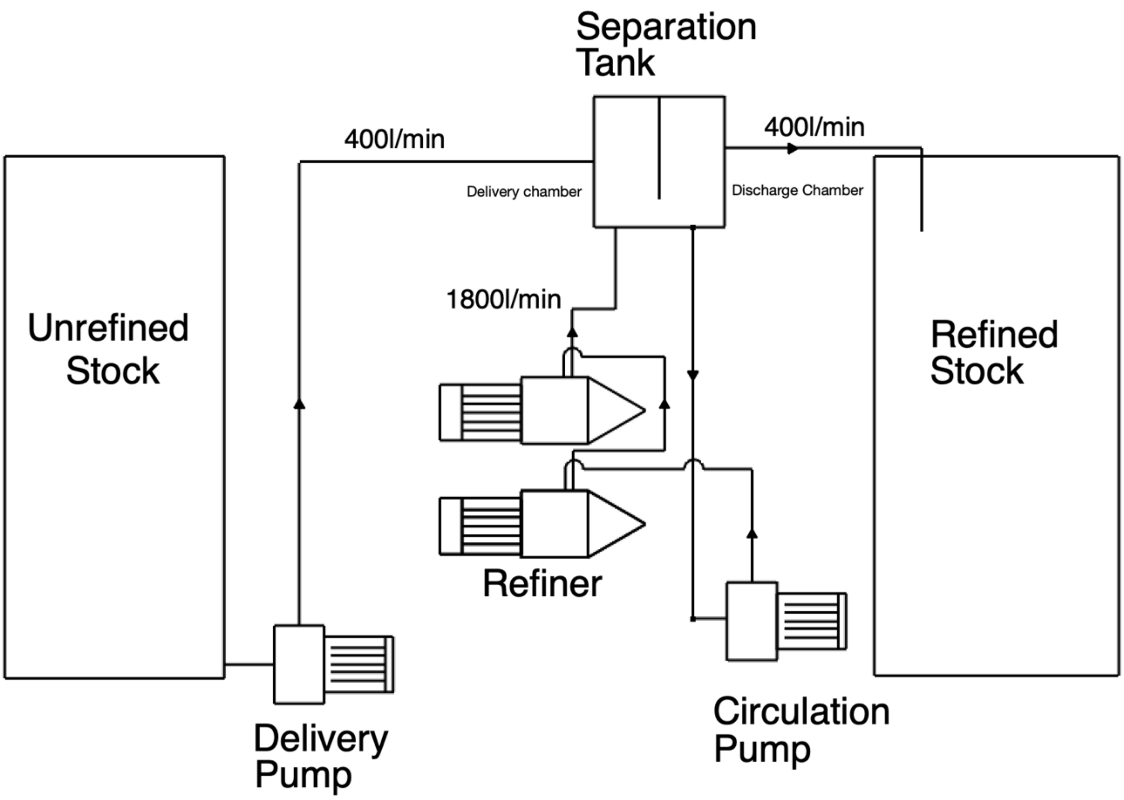


Figure 5: Pair of double disc refiners with separation chest

Factory	Pulp	Consistency	Refining System

2	Specially prepared P. Radiata pulp with Kappa number between 23-25	4.0% nominal in alkaline process water	2 conical refiners in series with passage from one tank to another until the desired freeness was obtained – circuitry also shown below

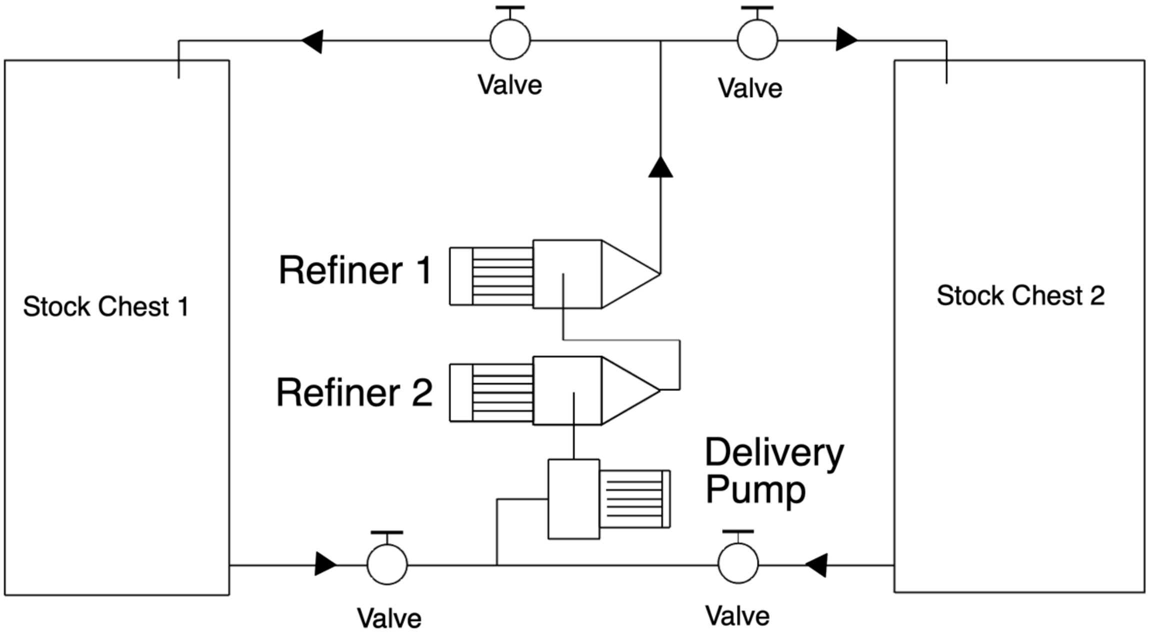


Figure 6: Pair of conical refiners set up to allow multiple passes from one stock chest to another.

The bar width and groove depth of the plates for the double disk and conical refiners were very similar as shown in Figures 7 & 8 below. So it may be inferred that the performance of each refiner set should be similar.

	
Figure 7 :double disk refiner Factory 1	**Figure 8 Conical Refiner Factory 2**

Preparation of the refined pulp.

Each pulp was first repulped in water in a standard pulper at moderate consistency and immediately prior to refining, the consistency was adjusted to the target consistency. At the termination of repulping, samples were taken for confirmation of consistency and SR. In each factory the flow rates of the pulp and the effective power imposed to the pulp within the system were controlled and it was possible to determine the total effective energy input imposed and the resulting SR.

In the case of Factory 1, the data are derived from an investigation of the effects of refining intensity and imposed energy on the SR developed and cutting of the fibre. Because of the "black box" nature of the system it was not possible to determine the changes of SR directly during its imposition, however there was a sufficient range of SR in the results that this was unnecessary.

In Factory 2, it was possible to determine the development of SR during refining because samples could be taken after each pass through the refiner from one tank to the other. Furthermore the factory had indulged in some experimentation with refining and a wide range of outcomes were encompassed. No changes were made to the intensity and the intensity is an estimate from the average of a number of runs.

Table 4: Results of Refining

Double Disc – Data Set 1			Conical – Data Set 2					
I J/m	E kWHr/t	SR	I J/m	E kWHr/t	SR	I J/m	E kWHr/t	SR
	0	12		0	12			
1.5	288	27	2.18	168	17	2.18	344	38
	341	28		180	17		360	41
	362	31		170	17		340	38
1.75	210	25		170	16		338	35
	256	27		170	17		340	38
	329	28		168	21		334	41
2	258	30		170	20		336	46
	316	34		170	19		336	42
	406	39		170	17		336	41
2.25	298	41		168	17		336	40
	364	56		170	22		336	48
	468	59		170	20		330	42
				156	15		314	38
				154	21		304	43
				150	17		300	38

Excel's graphing facility was used to provide a comparison of the results and to regress the SR on the total imposed refining energy with the following result after rescaling E_{eff} to MWHr/t.[7]

[7] The initial graphing of the response was done using SR vs E_{eff} expressed as kWHr/t where little difference was found between the regression coefficients of each data set. On rescaling the units to MWHr/t a larger difference was found in the coefficients. It seems that unless the independent and dependent variables are similar in magnitude, it is likely that Excel's graphing facility cannot discriminate very well between data sets. Caution is needed!

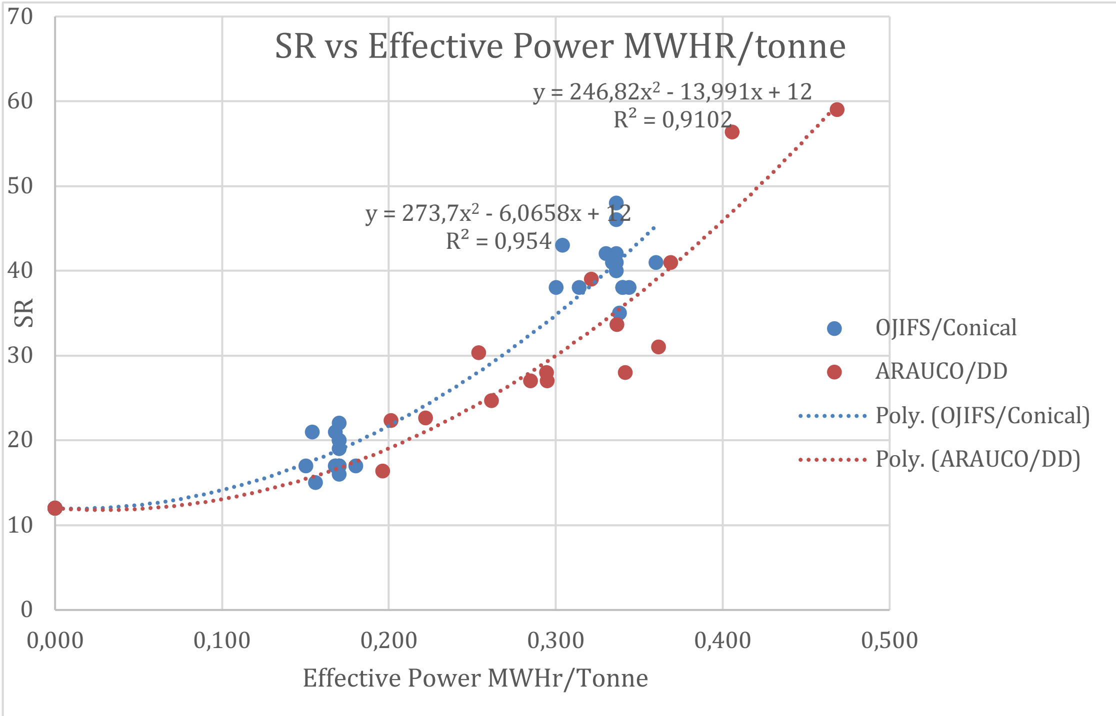


Figure 9: Refining comparison of conical and Double Disc Refiners

Restating the Regression Equations from the graph we obtain

Double Disc Refiner	$SR = 246.83E_{eff}^2 - 13.991E_{eff} + 12$	E = Energy MWHR/t	$R^2 = 0.9102$[8]
Conical Refiner	$SR = 273.7E_{eff}^2 - 6.0658E_{eff} + 12$	E = Energy MWHR/t	$R^2 = 0.954$

In both equations the coefficient of E_{eff} is small compared to the coefficient of E_{eff}^2 and we can ignore E_{eff} in the final equation. However, Figure 9 shows that in fact there is a big difference between the regression coefficients of the equations for the conical and double disc refining sets. In both case R^2 is nearly 1 confirming our contention of Part 1.

[8] The square of the correlation coefficient R^2 is a measure of the relationship between the variables with the value of 1 indicating perfect correlation and therefore causation is more likely with these high values for R^2

Refining Intensity

Since it was also likely that the refining intensity would have some effect the results of the double disc refining were individually examined with the results shown in Figure 10.

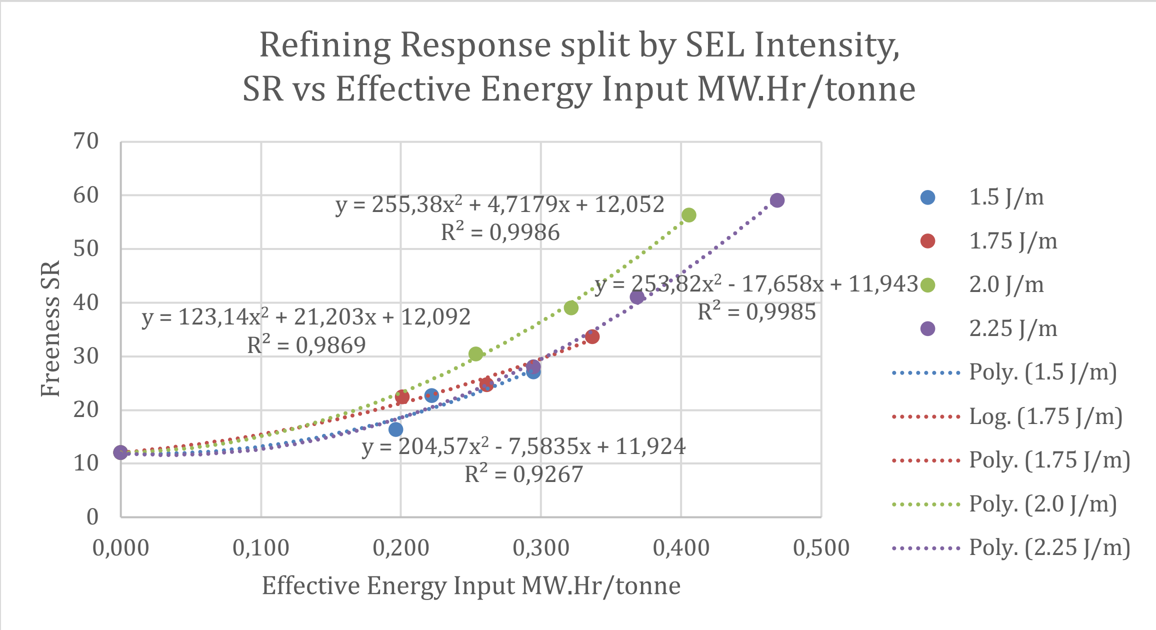


Figure 10: Refining response in DD refiner split by refining intensity

As can be seen the individual results show increasing response to increasing intensity of refining as indicated by the coefficients of the regression equations. The correlation coefficients (R^2) for each line are actually better than for the composite line as would be expected if the refining intensity is a contributing factor to refining response.

As inferred above it is clear that the magnitude of the product of E_{eff}^2 and its coefficient is much greater than the magnitude of E_{eff} and its coefficient and we therefore ignore E_{eff} as opposed to E_{eff}^2. Also the constant is equal to the SR of the unrefined pulp, so we can re-express the relationship between SR and specific refining energy in the form

$$SR - SR_0 = \Delta SR = k * E_{eff}^2 \text{ -------- } 3$$

where k = a constant and E_{eff} = the specific refining energy in MWhr/t

This was achieved in Excel by regressing[9] ΔSR against E_{eff}^2 the square of the effective refining energy and the results are shown graphically below for each of the levels of intensity.

As can be seen the response of change in SR to the square of refining Energy is linear and the correlation coefficients are all greater than those where E_{eff} and E_{eff}^2 are both included. The coefficients of Table 5 apply.

Table 5: Coefficients of E_{eff}^2 in Equation 3

Intensity J/m	Coeff of E_{eff}^2	R^2
1.50	174.22	0.9242
1.75	195.23	0.9723
2.00	268.89	0.9983
2.25	210.98	0.995

[9] We forced the regression through the point 0,0 by setting the intercept to 0.0.

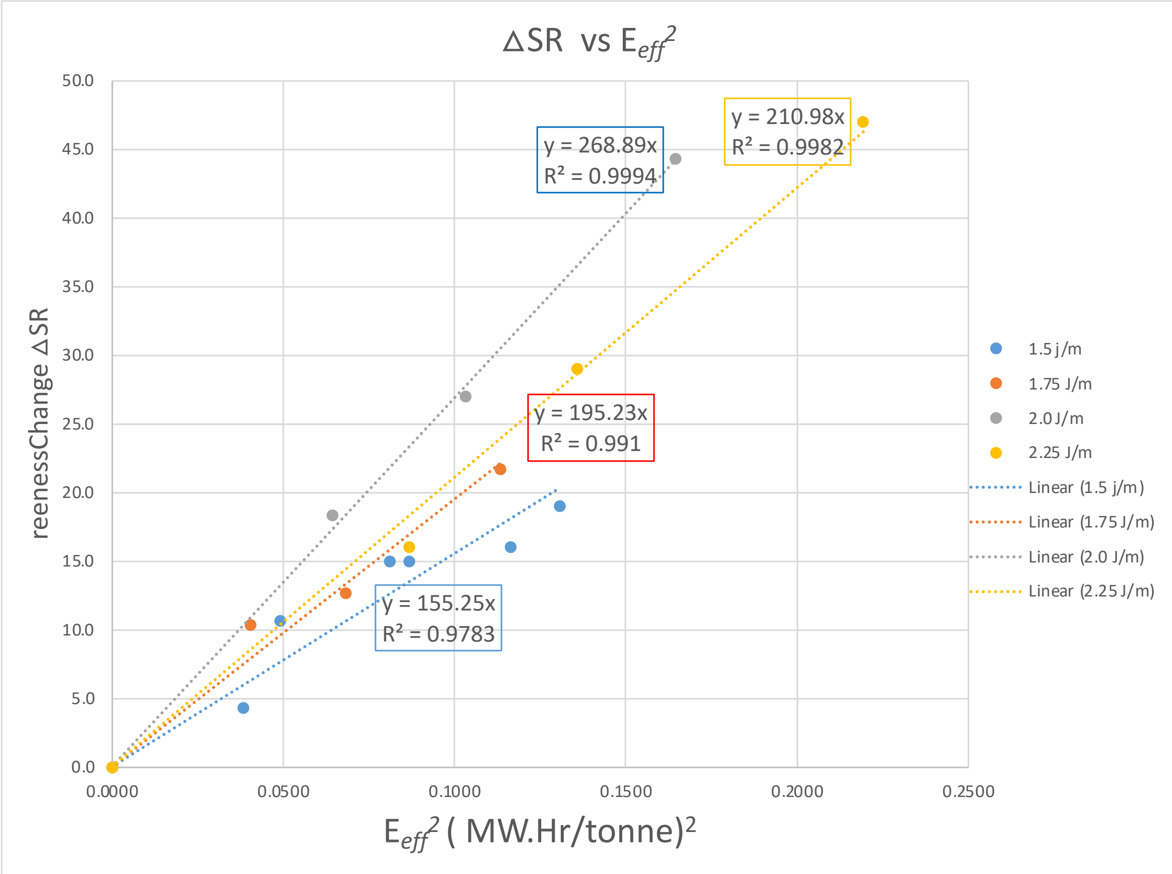


Figure 11: SR-SR0 vs Eeff2 at varying Refining Intensities

It was hypothesised that the coefficients would be linear with respect to refining intensity and we examine this in the Figure 12 below using the data from Table 5.

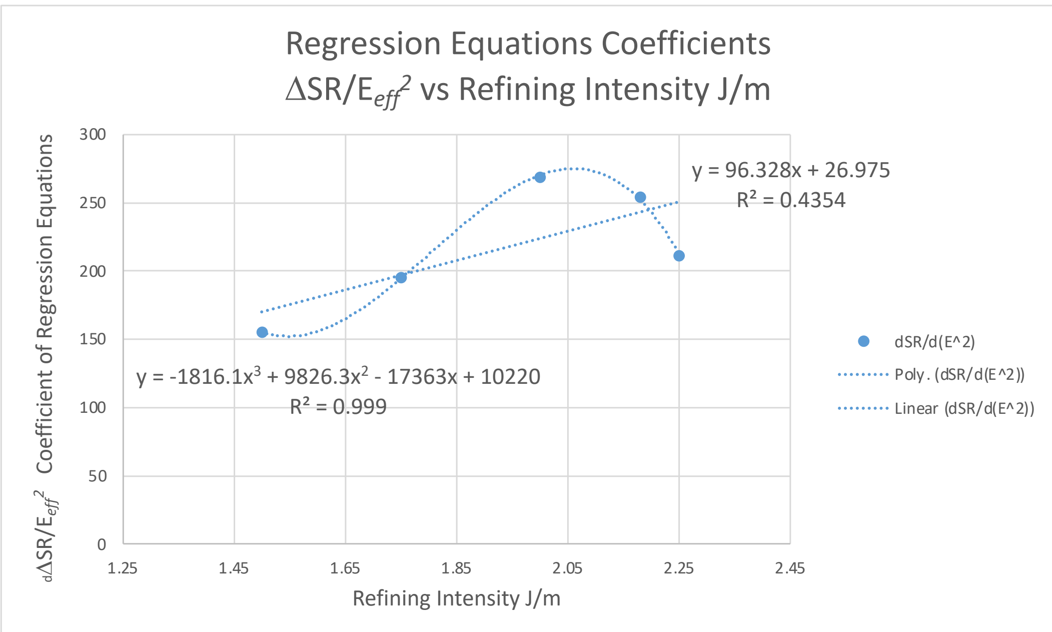


Figure 12 Regression Equations for Change in SR vs Refining Intensity

It will be clear from the input data that there is an anomaly in the proportionality of the coefficients of $\Delta SR/\Delta E_{eff}^2$ to the effective applied power at high intensity. So in this case we are not justified in using the regression equation. We can however obtain a polynomial relationship from which we can calculate the coefficients. This relationship is,

$$\Delta SR/\Delta E_{eff}^2 = -1762.8*I^3 + 9524.1*I^2 - 16801*I + 9877.5 \qquad 4$$

The correlation coefficient of this relationship is extremely good ($R^2 = 1$) and while this indicates all of the relationship is described by this equation it should be noted that the relationship is entirely empirically derived.

However if we substitute the relationship into the refiner response equation we can rewrite the refiner response equation as

$$\Delta SR = SR - SR_0 = (-1762.8 * I^3 + 9524.1 * I^2 - 16801 * I + 9877.5) * E_{eff}^2 \qquad 5$$

where $SR_0 = 12$ and

I = refining intensity

This can now be tested in two ways.

1. Take the information from the double disc refiners and calculate the response of the pulp to the refining energy. Regress the relationship found and assess this by the slope of the trendline (should be 1) and value of R^2.
2. Add in the same data from the Conical refiner assuming that is also has the same coefficient. Determine its trendline slope and R^2 as above.
3. Combine all of the data from both refining systems and determine the combined trendline slope and R^2 also as above.

The results are shown in the Figure 13 below.

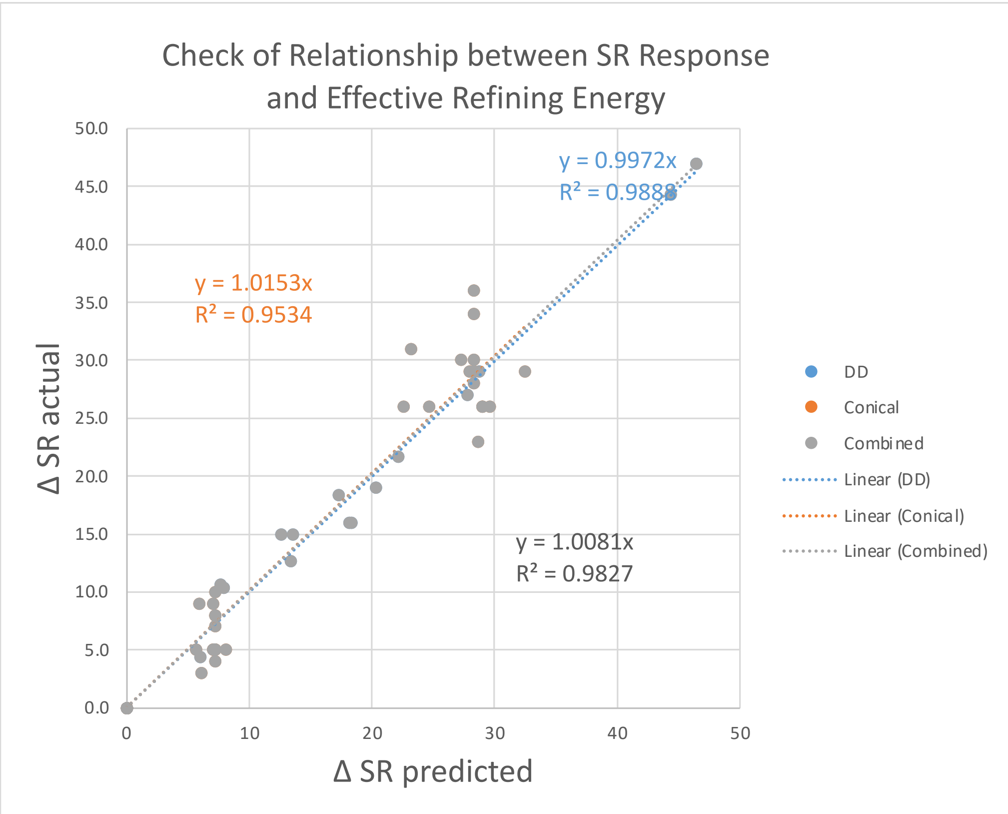


Figure 13: Check of relationship between SR Response and Effective Refining Energy

In Figure 13 we have combined 3 sets of data.

1. The original data from the double disk refiner which was used to derive the relationship
2. The data from the conical refiner and
3. The combined data of the double disk and conical refiners.

For each we have obtained a linear trendline forced through the point 0,0 and displayed on the graph the equation of the line and the correlation coefficient. We obtained the following results

Table 6: comparison of performance of predictions of Equation 4 and 5

Data	Slope	Correlation Coefficient R^2
Double Disc	0.9972	0.9888
Conical	1.0153	0.9534
Double Disc and Conical	1.0081	0.9658

Since the equation for the relationship between E_{eff}^2,SEL and freeness was derived from the double disc data, it is not surprising that it has a slope that is closest to 1 and the highest correlation coefficient. However, we could also use this equation for the conical refiner set and the combined data sets are within 1% of the expected value of the slope of 1 which indicates perfect correlation.

Data Set 3 – OJIFS K25 P Radiata pulp

Table7 lists an abstract from the data provided by OJI Fibre Services for refining response of their K25 pulp that is specially manufactured for fibre cement from selected P Radiata wood chips.

The columns list the freeness of the pulp after refining to specific energy inputs at specific intensities of refining[10]. There are also columns indicating the temperature rise of the pulp after completion of refining, fibre length (length weighted), fibre fines i.e. the proportion of the fibres passing a 200# screen. The data includes two columns of data calculated from the primary data – these are the change in freeness during refining and the square of the effective energy input expressed as $(MW.Hr/tonne)^2$. We use these figures to analyse the response of the pulp to refining.

The change in freeness can be measured directly for each of the particular refining intensities because we have the starting freeness of the pulps. By subtracting the refined CSF from the unrefined CSF in each case we obtain a number that increases as the energy input increases thus the shape of the curves is similar to those derived from SR but of course the coefficients relating change in CSF with E_{eff}^2 are different from those relating change in SR with E_{eff}^2.

[10] Refining Intensity in the table is shown as W.s/m – this is exactly the same as J/m.

Table 7: OJIFS Data for K25 Pulp

Specific edge load Ws/m	Temp rise oC/min	Energy input kWhr/t	Freeness	Fibre Length	Fines	Change in Freeness	Energy input (MWhr/t)^2
			740	3.02	2.43	0.00	0.00
0.346	1.8	90.3	727	3.02	2.65	13.00	0.01
0.346	1.8	210.5	680	3.07	2.32	60.00	0.04
0.346	1.8	361.1	675	2.98	3.01	65.00	0.13
0.346	1.8	541.7	460	2.97	3.12	280.00	0.29
			760	3.04	2.24	0.00	0.00
0.987	2.07	81.4	690	3.01	2.65	70.00	0.01
0.987	2.07	162.6	610	2.95	2.82	150.00	0.03
0.987	2.07	244.2	486	2.83	3.45	274.00	0.06
0.987	2.07	325.1	348	2.74	3.68	412.00	0.11
			765	3.04	2.48	0.00	0.00
0.424	1.84	109.2	706	3.01	2.66	59.00	0.01
0.424	1.84	215.2	621	2.93	2.96	144.00	0.05
0.424	1.84	322.6	553	2.78	3.67	212.00	0.10
0.424	1.84	429.9	431	2.63	4.05	334.00	0.18
			745	3.05	2.27	0.00	0.00
1.636	2.28	108.9	652	2.83	3.06	93.00	0.01
1.636	2.28	190.5	512	2.64	3.56	233.00	0.04
1.636	2.28	272.0	350	2.42	4.33	395.00	0.07
1.636	2.28	326.3	270	2.33	4.62	475.00	0.11
			770	3.05	2.19	0.00	0.00
2.106	2.48	105.1	666	2.71	3.11	104.00	0.01
2.106	2.48	184.1	500	2.45	3.74	270.00	0.03
2.106	2.48	263.1	316	2.15	4.56	454.00	0.07
2.106	2.48	315.5	240	2.06	4.97	530.00	0.10

If we graph freeness against effective refining energy E_{eff} we obtain Figure 14.

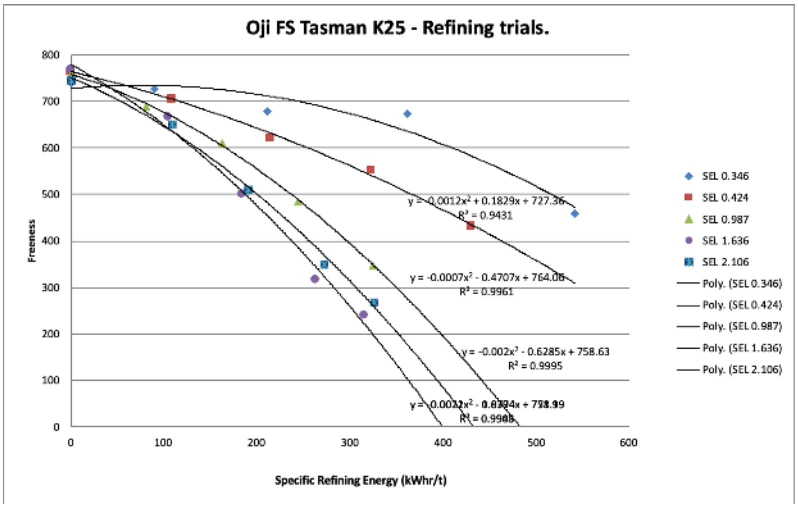


Figure 14 Freeness vs Effective Refining Energy kWHr/tonne OJIFS K25

As can be seen the graphs of the individual freeness energy response curves are concave downwards and their trendlines are high correlated when their curves are expressed as CSF vs E_{eff}^2. So we are justified in taking the same approach as with the previous examples where SR is used as the measure of freeness. The results are shown in Figure 15 where we plot the change in freeness from the unrefined pulp against the equivalent applied E_{eff}^2.

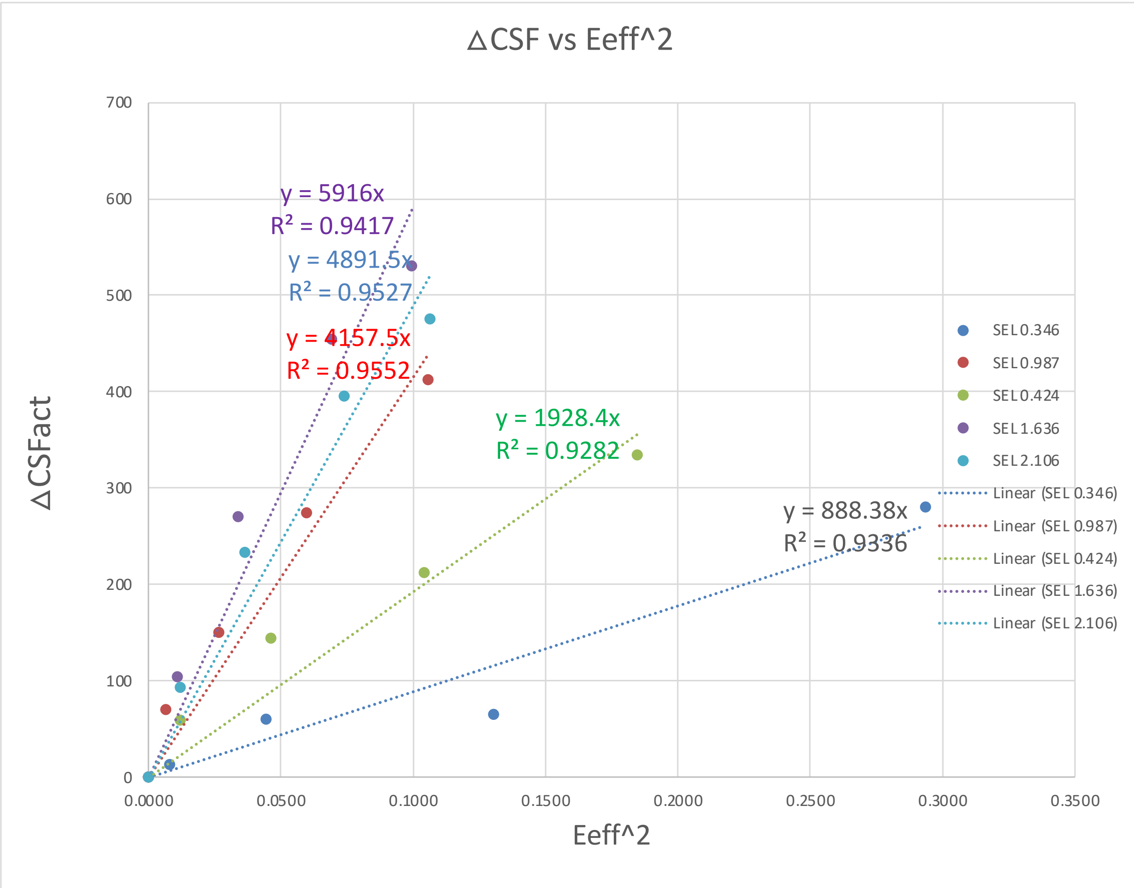


Figure 15 Change in CSF vs Eeff2

If we extract the coefficients of the regression lines, we obtain the following table 8.

Table 8 Coefficients of Effective Refining Energy at differing refining Intensities

SEL	Coeff Eeff^2	R^2
0.346	888.38	0.9396
0.424	1928.40	0.9282
0.987	4157.50	0.9552
1.636	5916.00	0.9417
2.106	4891.50	0.9527

It is seen that at each of the intensities the trendline fairly represents the relationship between the intensity and the rate of change of freeness with well correlated E_{eff}^2. We can therefore see if we can discover a relationship between the coefficients $(\frac{\Delta CSF}{E_{eff}^2})$ and the Intensity of refining (SEL). Graphing the result in Figure 16 and determining two types of relationship between Intensity and the coefficients we get the following.

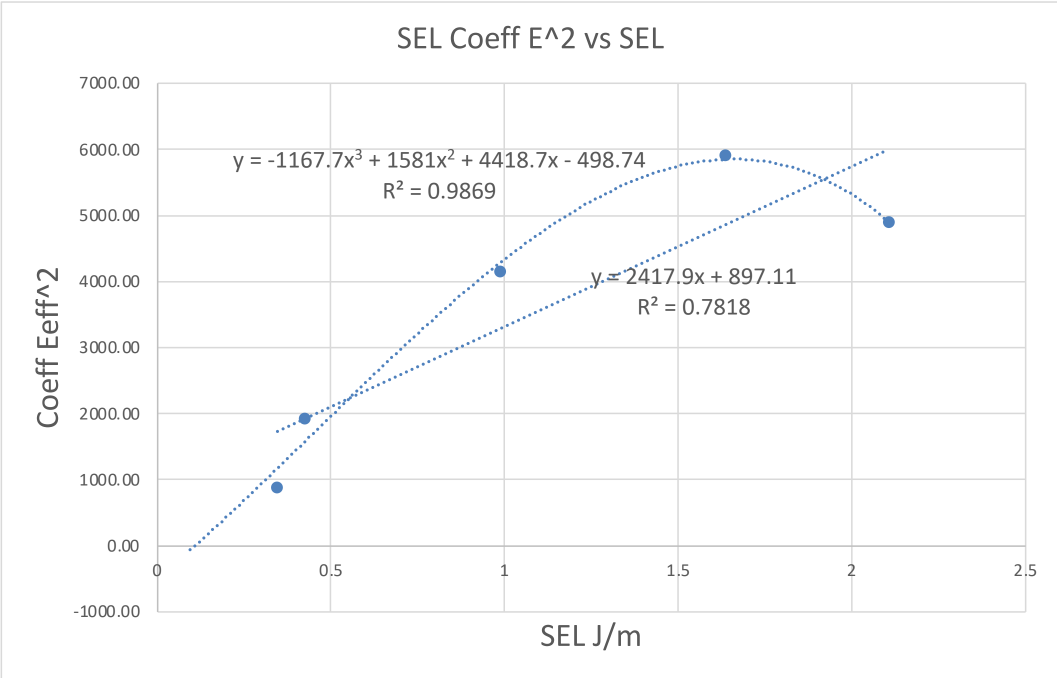


Figure 16 Coefficient of Eeff2 vs Refining Intensity

We can see that the linear relationship does not describe the possible relationship between refining intensity and $(\frac{\Delta CSF}{E_{eff}^2})$ as well as the more complex polynomial relationship which better reflects the drop of efficacy of refining when attempting to refine at high intensity. In the original work on SR the same effect occurred and was originally suspected to result from a mistake in the collection of the data. However, since this also occurs in this data and $\frac{\Delta CSF}{E_{eff}^2}$ for the conical refiner dropped neatly between the higher intensity values for the double disk refiner it is accepted that this represents a real effect and should be explained when assessing the results.

Taking these results we can therefore write a relationship of the following types to predict the change in CSF with input of refining energy.

Linear $$\Delta CSF = (2417.9 * I - 897.11) * E_{eff}^2 \quad 6$$

Polynomial $$\Delta CSF = (-1167.7 * I^3 + 1581 * I^2 + 4418.7 * I - 498.74) * E_{eff}^2 \quad 7$$

We check the accuracy of these equations by calculating ΔCSF from the equations above and comparing the result with the actual ΔCSF that was observed. As in the earlier analysis, the slope of the trendline should be 1 if the predicted and observed are on average equal and the regression coefficient will provide a measure of the fit of the regression. The next graph shows the results of this exercise for both prediction equations.

The polynomial prediction equation provides a slightly more accurate prediction than the linear equation although both equations have slopes within 1% of equality. In other words we could use the linear equation to predict freeness changes with refining although it would be in slightly greater error than the polynomial equation.

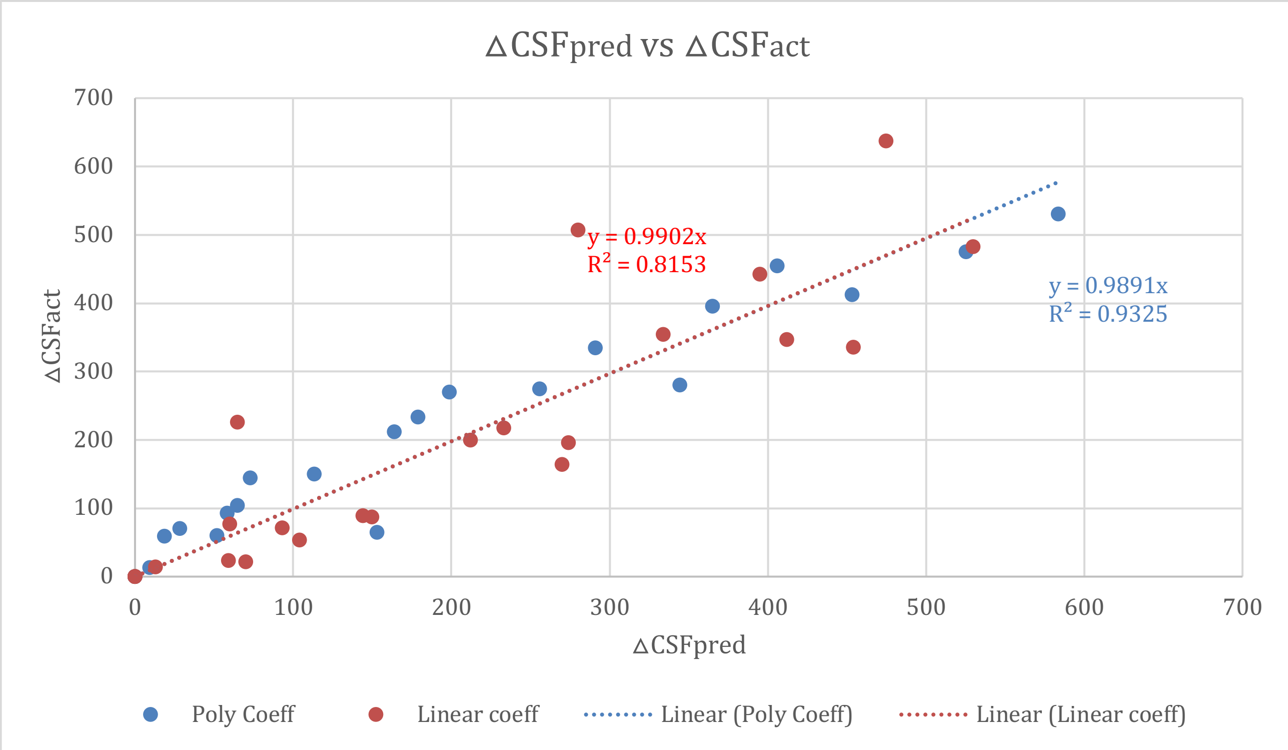


Figure 17 Comparisons of Predictions of Changes in CSF vs Observations

Significance of the Empirical Equations for calculating the Coefficients of SEL in the relationship between Freeness and Imposed Effective Energy of Refining and the Reduction in Refining Efficiency at High SEL levels

Not too much should be made of the empirically derived equations for the SEL coefficients for several reasons. Firstly there is no physically derived method to justify the shape of the equations even though three different sets of refiners demonstrate a similar shape. The implication of the shape however is that there is a lower levels of refining intensity where no refining takes place and at some upper level of SEL, refining is compromised as measured by the reduction in the coefficients of the higher SEL levels compared to the immediately lower level.

Having said that, the CSF files indicated that the minimum SEL was around 0.11 J/m and that it maximised at 16 J/m. Clearly this last result is not significant as it would not be possible to reach this SEL level. The SR equation has no lower roots but since the first 3 results are nearly linear we can use a linear relationship to interpolate to the minimum SEL which is around 0.85 J/m. While they are broadly similar in their peaks and minima, this can only be indicative.

The SEL levels are determined from the edge length of the bars of the refiner set and the power imposed on the pulp by the refiner. Mrozinski[vi] presented information on plate clearance and power requirements for a double disc refiner set and after manipulation of the data it was found that a relationship between power requirements of the refiner and the plate clearance was

$$P = K_1 . \ln\left[{}^{1}/_{C}\right] - K_2 \qquad 8$$

where P = Power required

C = plate clearance and

K_1 and K_2 are empirically derived constants

Equation 8 shows that the power rises with the reduction in plate clearance but rises more or less asymptotically to a limiting value. Clearly at a clearance of 0 mm the power would increase to infinity but of course this is not possible. Nevertheless there will come a point where the gap is such that the fibre cannot be drawn into the gap as may be inferred from the Figure 18 taken from Mrozinski (Figure 2). At this point the efficacy of the refiner is reduced and the coefficient of the equation for SEL and fibre refining will drop.

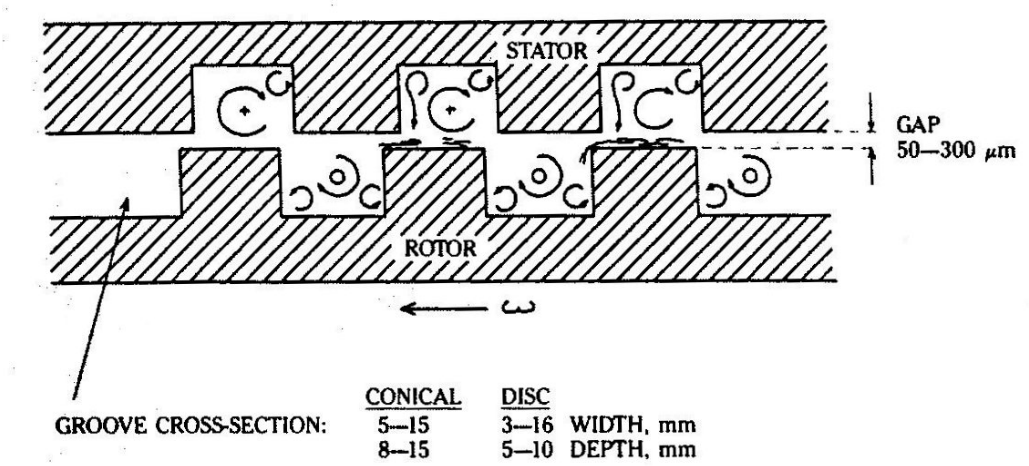


Figure 18: fluid flow within the grooves of a refiner (from Mrozinski).

Conclusions of Part 1

1. There is a broad general relationship between freeness as measured by change in either CSF or SR and the square of the applied effective refining energy.
2. The relationship is explained by the fact that the freeness is proportional to the square of the specific surface area of the fibre.
3. The change in specific surface area of the fibre is therefore proportional to the input of effective refining energy. In other words the applied effective refining energy can provide an indication of the change of specific surface area of the fibre.
4. While the specific surface area of the fibre is developed by refining, there is no way of determining the means by which the surface area increases. Since this is measured by a filtration method, one cannot determine whether specific surface area is increasing due to internal fibrillation, external fibrillation, fibre splitting or by peeling as a film of the outer layers of the fibres. This can only be determined by microscopic examination.
5. SEL determines the rate at which specific surface is developed but there seems to be a point where the refiner chokes i.e. the gap as shown in figure 18 is so narrow that fibres are unable pass in bundles between the bars of the rotor and stator. Thus it becomes more difficult to increase specific surface of the fibres at this point and the efficiency of the refiner drops. It is likely that the choke level is determined by the refiner plate configuration and this justifies further investigation.

Appendix to Part 1: Specific Edge Load or Refining Intensity

Olejnik[vii] et al have descried the development of criteria for characterising cellulose pulp refining as follows.

> "*At the moment, only a few criteria, which describe refining processes, exist and are universally accepted by the scientists. The most popular criteria are cutting edge length (CEL) and specific edge load (SEL), which were introduced by Wultsch and Flucher (1958) and later supplemented by Brecht and Siewert (1966). Apart from that, specific energy consumption (SEC) is also commonly used.*
>
> *CEL is defined as,*
>
> $$CEL = z_R \cdot z_S \cdot l \frac{n \cdot}{60}, [m/s]$$
>
> *where* z_R *is the number of rotor bars,* z_S *is the number of stator bars,* l *is the bar effective length [m], and* n *is the rotational speed of refiner rotor [rpm]. On the other hand, SEL can be calculated according to the formula:*
>
> $$SEL = \frac{P_{net}}{CEL}, [J/m]$$
>
> *where* P_{net} *is the effective refining power [W] and CEL is the cutting edge length [m/s]. SEL defines the amount of effective refining energy transferred by the edges of refining elements to the refining zone. SEL is currently considered to be the most reliable parameter when analysing refining processes".*

As can be seen, the CEL is characteristic of the refiner and the SEL depends on the refiner and how it is operated. Most refiners will operate at constant rotational speed and the power at which they operate is determined by the operator by closing the gap between the refiner blades.

CEL and SEL are therefore means by which we can compare the operation of different refiners providing that we can set them as similar SEL's.

The actual response of the pulp to refining will be determined by the characteristics of the pulp itself and we would need to develop equations similar to those above to determine the coefficients of the equations. Once we have these for a specific pulp we can use those equations to set up our refiners for specific outcomes.

ACKNOWLEDGEMENTS

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IIBCC

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