

The response of mechanical and chemical pulps to refining

K. B. Miles and A. Karnis

Research scientist and division director, Pulp and Paper Research Institute of Canada, 570 St. John's Rd., Pointe Claire, Quebec, Can. H9R 3J9

ABSTRACT *Theoretical equations describing the flow of pulp in refiners were used to analyze the experimental results obtained in a series of pilot plant trials. Western red cedar and loblolly pine wood chips were refined in 1–3 stages at rotational speeds of 1200 and 1800 rpm to produce thermomechanical pulps (TMP). Also, sulfate semibleached and low-yield sulfite pulps were refined at low (5%), medium (12%), and high (25%) consistency. The results indicate that the number of refining stages did not affect mechanical pulp quality. At a given specific energy, increasing the rotational speed increased the specific energy per impact and decreased the total number of impacts, resulting in a faster rate of fines generation for mechanical pulps. For chemical pulps higher pulp consistency produced gentler refining and yielded a higher rate of freeness decrease.*

KEYWORDS

Chemical pulps
Consistency
Energy
Mechanical
pulps
Pulping
Refining

Beating and refining are the processes used to develop the papermaking properties of fibers. In the process, energy is absorbed by the fibers through the repeated cyclic compression and decompression imparted to the fibers by the bars of the refiner plates. Fibers are subjected to a complicated pattern of shearing and compressive forces, which cause both internal and external fibrillation.

Refining intensity has been recognized as an important parameter in both low-consistency stock refining and high-consistency chip refining (1–7). At a given specific energy, the residence time of the material in the refining zone determines the number and intensity of impacts delivered to the fibers by the bars of the refiner plates.

The concept of characterizing the refining action by two parameters, rather than by only one—the average specific energy—was first suggested by Brecht and later developed by Danforth, Nissan, and Arjas (4–7). Kerekes has recently reviewed these developments for low-consistency stock refining and extended the Leid-

er-Nissan analysis by introducing the concept of C-factor (3).

The analysis of the high-consistency chip refining operation has led recently to the development of a set of equations through which the residence time of the pulp in the refiner, τ , the total number of impacts, n , the specific energy per impact, e , and the specific refining power, e' , can be calculated (1, 2). If the steam flow term in the equation is neglected, the form of the equation is simplified so that the refining intensity can be calculated from the design and operating parameters of the refiner. This form of the equation has been used successfully to analyze mechanical pulping data from the pertinent literature (2).

If the pulp flow equations without the steam flow terms are successful in predicting the pulp properties for mechanical pulps, they can be applied with equal success to low-energy stock refining. It is postulated that for a given fiber and type of pulp, physical and optical properties are determined by the values of n and e . This postulate

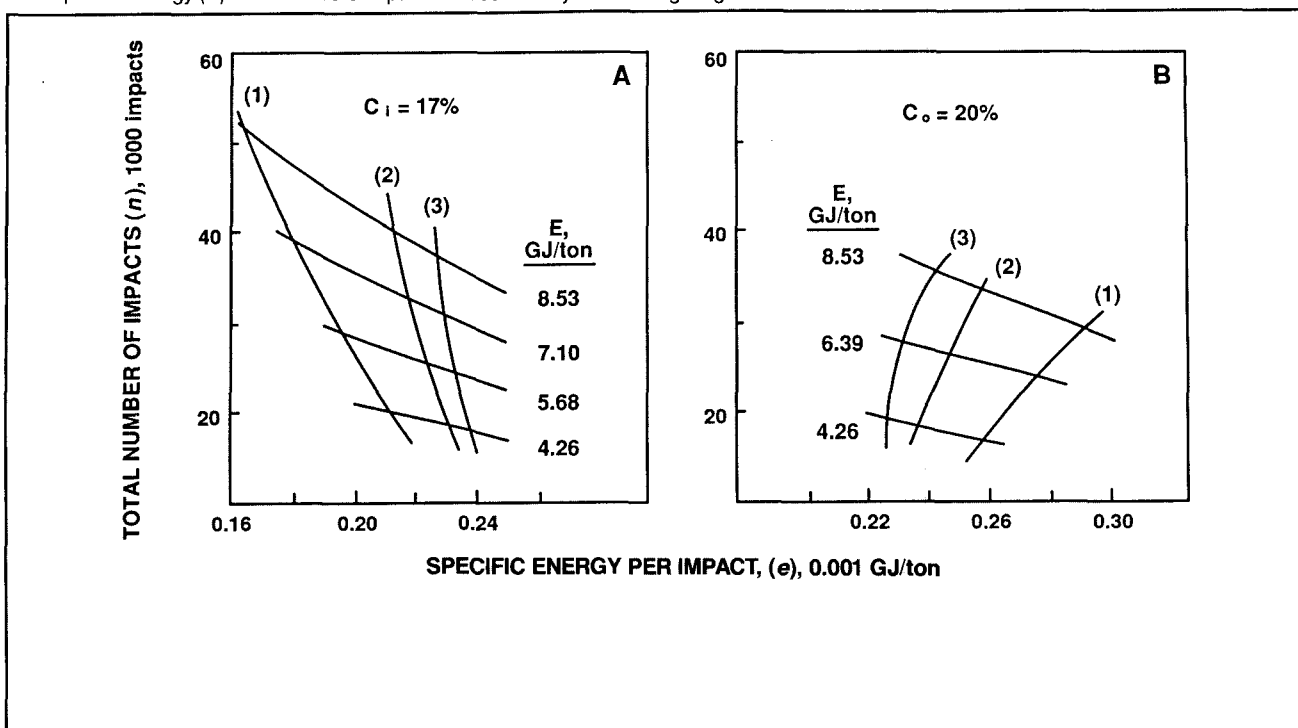
implies that a unique correlation exists between n and e values and pulp properties regardless of how the values of n and e were obtained. These values are affected by changing the size and type of refining equipment, the rotational speed, the refining consistency, or the number of refining stages. Some of these factors have been studied in low-consistency, low-energy refining of mechanical pulps.

In this report, the refining of both mechanical and chemical pulps was examined and the experimental results were analyzed in light of the pulp flow theory (1).

Theoretical considerations

An analysis of the forces acting on the material during high-consistency refining of wood chips gives an equation describing the flow of pulp in the refining zone along the radial direction (1). To extend the analysis to include the refining of chemical pulps at low specific energy, it is appropriate to take into account the Coreolis effect (2 $\mu_r\omega$). At high values of E

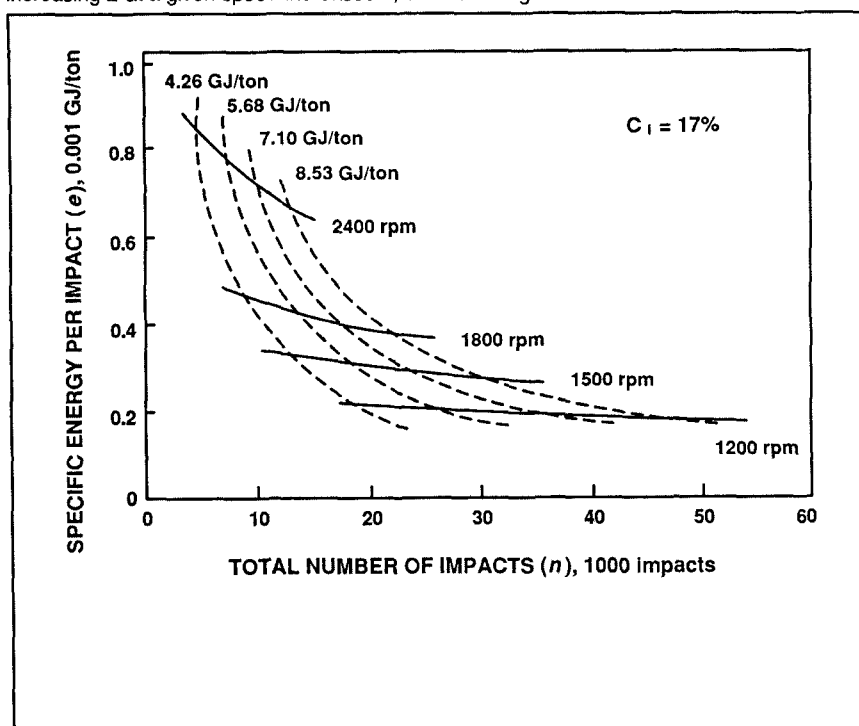
1. At $C_i = 17\%$ and $\omega = 1200$ rpm, an increase in the number of refining stages at constant E increased e and decreased n (A). In contrast, when C_o was constant at 20% , a multistage refining system operated at lower intensity compared to single stage operation at the same total specific energy (B). The numbers in parentheses identify the refining stage.



1. Refining conditions and pulp properties

Rotational speed, rpm	1800	1800	1800	1200	1200	1200
Specific energy, GJ/ton						
First stage	3.26	3.26	3.26	3.26	3.26	3.26
Second stage	4.32	3.04	1.53	4.85	3.42	2.20
Third stage	...	1.48	1.53	...	1.73	1.55
Fourth stage	...	...	1.38	...	...	1.44
Total	7.78	7.78	7.70	8.11	8.41	8.45
Discharge consistency, %	20	20	20	20	20	20
Residence time, s	0.97	1.0	1.0	1.7	1.8	1.9
Total number of impacts, in thousands	20.6	21.5	21.7	31.8	34.3	35.5
Spec. energy per impact, GJ/ton	0.000366	0.000360	0.000353	0.000255	0.000245	0.000238
Spec. power per impact, GJ/ton per s	7.8	7.8	7.7	4.7	4.7	4.4
Freeness, mL CSF	73	73	63	71	104	125
L-factor, %	39	34	30	50	52	54
Somerville shive, %	0.22	0.08	0.02	0.58	0.38	0.22
Linting index	0.15	0.33	0.26	0.18	0.10	0.01
Density, kg/m ³	410	435	438	424	418	392
Burst index, kPa·m ² /g	1.5	1.6	1.5	2.3	2.5	2.1
Breaking length, N·m/g	35	37	37	45	45	41
Tear index, mN·m ² /g	6.4	5.7	4.9	7.3	8.3	8.4

2. The effect of E and ω on n and e . The solid lines are the iso-speed lines, and the broken lines are the iso-energy lines. At a given E , increasing ω increased the intensity of refining. Increasing E at a given speed increased n , but the change in e was minor.



(mechanical pulping), the term $(2\mu_r\omega)$ is small compared to that including E and can be neglected. The complete equation of flow, which includes refining at both low and high energy, is:

$$\frac{dV}{dr} = r\omega^2/V - 2\mu_r\omega - a(\mu_r/\mu_t)EC/[\omega(r_2^2 - r_1^2)] \pm 1/2 c_p U^2 Ap (C/V) \quad (1)$$

where

V = radial velocity of the pulp at radius r

ω = angular velocity of the disc

μ_r = friction coefficient between pulp and disc in the radial direction

μ_t = friction coefficient between pulp and disc in the tangential radial direction

E = specific energy

C = consistency at radius r

r_1 = inner radius of the refining zone

r_2 = outer radius of the refining zone

c_t = steam friction coefficient

p = density of steam

U = steam velocity at radius r

Ap = the aerodynamic specific surface.

The term a is a constant dependent on the refiner configuration. The value of a is 4 for a single-disc and 2 for a double-disc refiner. The positive and negative signs in the steam flow term reflect the effect of steam on V in the forward and backward flow regimes, respectively.

Assuming that the effect of the backflowing steam in decelerating pulp flow is approximately balanced by the effect of the forward flowing steam in accelerating flow, Eq. 1 reduces to:

$$\frac{dV}{dr} = (r\omega^2/V) - 2\mu_r\omega - a(\mu_r/\mu_t)EC/[\omega(r_2^2 - r_1^2)] \quad (2)$$

The average residence time of the pulp in the refiner is

$$\tau = \int_{r_1}^{r_2} dr/V \quad (3)$$

and the total number of impacts that a fiber receives during its passage through the refiner is

$$n = \int_{r_1}^{r_2} Nr\omega dr \quad (4)$$

where N = bars per unit of arc length.

The total applied specific energy, E , is given by either

$$E = ne \quad (5)$$

where e is the specific energy per impact, or

$$E = \tau e' \quad (6)$$

where e' is the specific refining power. Equations 5 and 6 are equivalent; e and e' indicate the intensity of refining, whereas the residence time determines the number of impacts n for a given refiner plate pattern.

Equations 2-6 were used to correlate pulp quality data obtained in a pilot plant chip refiner (2). The refiner operated in a single-stage, atmospheric discharge mode, producing refiner mechanical pulp.

In the case of stock refining, the energy applied is low, and the steam term in Eq. 1 can be neglected. Stock refining includes low- and high-consistency refining of chemical pulps and post refining of mechanical and high-yield pulps.

Mechanical pulps

Experimental procedures

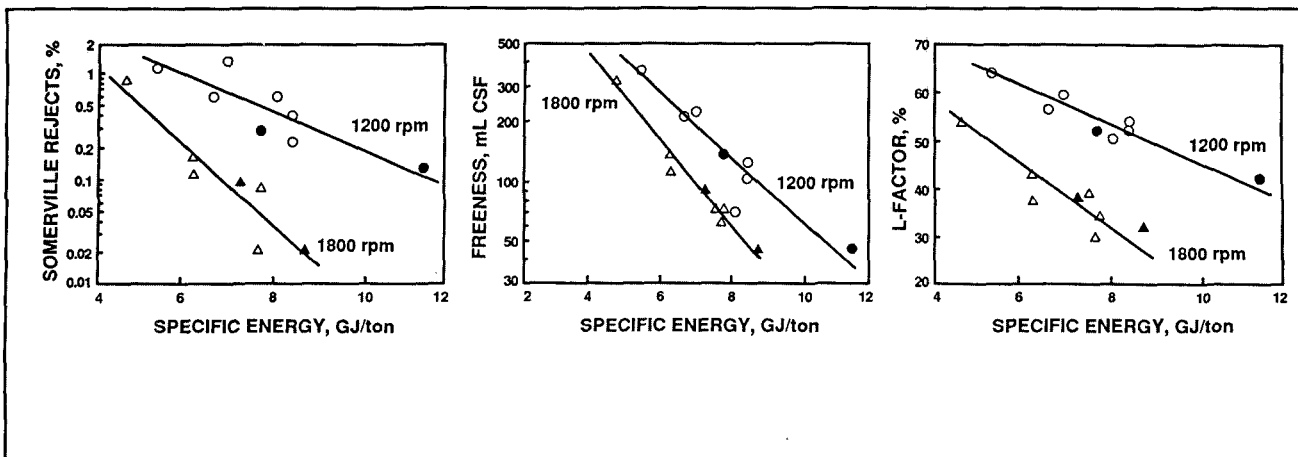
The pilot plant refining trials were carried out in the Sprout-Bauer Laboratory. Thermomechanical pulps were prepared from western red cedar and loblolly pine wood chips (8). The refining system consisted of a first-stage, pressurized, double rotating disc refiner, 914.4 mm in diameter (36 in., Bauer Model 418), operating at 1200 rpm. The second-stage refining was done in an open-discharge, double rotating disc refiner (Bauer Model 401, 914.4 mm in diameter), which operated either at 1200 or 1800 rpm. Second-stage refining was carried out in one, two, or three passes. Discharge consistency in all refining stages was maintained in the range of 20-21% (8). Pulp and handsheet testing was performed in accordance with TAPPI methods. Linting indices were determined by the method described by Wood and Karnis (9).

The number of refining stages

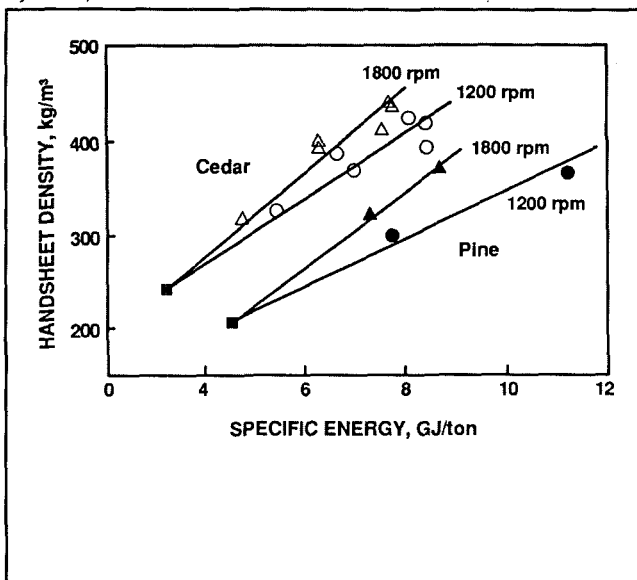
The second-stage refining of the mechanical pulps was carried out at two rotational speeds and in 1-3 passes. The energy input to each stage in the multipass refining operation varied, but the total specific energy was the same in all the experiments.

The equations of flow can be used to calculate the refining intensity at each stage and at each level of rotational speed. For multipass refining,

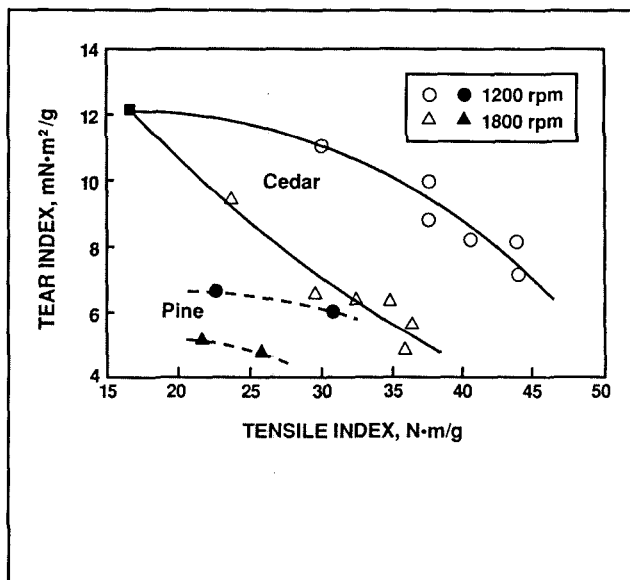
3. Somerville shive, freeness, and long fiber content (L-factor) decreased faster with specific energy at 1800 rpm than at 1200 rpm. (Open symbols: cedar TMP. Filled symbols: pine TMP.)



4. Sheet density increased with increasing E . For a given E and wood species, sheet density was higher at 1800 rpm than at 1200 rpm. Density was higher for cedar (open symbols) than for pine (filled symbols) TMP.



5. At a given tensile strength, tear strength was lower for TMP made at 1800 rpm; it was also lower for pine TMP than for cedar.



τ is the total residence time in all stages, and n is the total number of impacts. For a total specific energy, E , e is then E/n , and e' is E/τ .

Figure 1A shows the changes in n and e calculated from Eqs. 2-6, assuming a constant inlet consistency, C_i , of 17% and an equal energy application in each pass. Figure 1B shows the same calculations done at a constant outlet (discharge) consistency, C_o , of 20%. Figure 1 shows that increasing the number of passes decreased the range of both n and e for a given change in specific energy. This effect was found whether refining was done at constant inlet or

constant outlet consistency. However, the mode of operation, constant C_i or C_o , affected the n and e values at a given E .

When C_i was kept constant at a given E , a single-stage refining operation gave a gentler refining (i.e., higher n and lower e) than a multistage (or multipass) operation (Fig. 1A). At first, this finding may appear surprising, but the explanation lies in the fact that for constant C_i the average refining consistency is higher in a single stage than in a multistage operation because greater energy is applied. An increase in consistency results in longer residence time,

which implies that the refining is of lower intensity. The situation was reversed when refining was done at constant C_o ; increasing the number of stages resulted in gentler refining (Fig. 1B).

Interestingly, the data in Fig. 1 illustrate how relatively small changes in consistency and mode of operation affect refining intensity. This finding may explain some apparently contradictory results in the early literature on TMP regarding single-stage vs. two-stage refining and the effect on pulp properties of energy split between the refining stages.

Table I shows the calculated values

II. Change in pulp properties per GJ of specific energy per ton, showing the effect of rotational speed (1200 and 1800 rpm) and wood species

	Cedar		Pine	
	1200	1800	1200	1800
Shives, %	-0.16	-0.5	-0.16	-0.5
L-factor, %	-5	-12.5	-5	-12.5
Freeness, mL CSF	-98	-147	-98	-147
Linting index, wt. fraction	-0.16	-0.16	...	...
Sheet density, kg/m ³	30	36	25	27
Breaking length, N·m/g	5.9	4.5	2.2	2.2
Burst index, kPa·m ² /g	0.37	0.23	0.17	0.17
Tear index, mN·m ² /g	-0.83	-1.7	...	...

Thermomechanical pulps: discharge consistency of 20–21%.

III. Comparison of cedar and pine TMP

Operating conditions and pulp properties	Cedar	Pine
Specific energy, GJ/ton	7.8	11.3
Rotational speed, rpm	1800	1200
Discharge consistency, %	20	20
Residence time, s	1.2	4.3
Total number of impacts	19,000	76,000
Specific energy per impact, GJ/ton	0.0004	0.00015
Specific power per impact, GJ/ton per s	6.5	3.2
Freeness, mL CSF	73	46
Shive, %	0.08	0.12
L-factor, %	34	42
Density, kg/m ³	435	365
Burst index, kPa·m ² /g	1.6	1.4
Breaking length, N·m/g	37	32
Tear index, mN·m ² /g	5.7	6.1

of τ , n , e , and e' based on the unpublished results of Sinkey (8). The table also gives the pulp and handsheet properties. At a given n , e , and E , pulp properties appear to be independent of the number of refining stages. It is not sufficient that only the total specific energy in all stages be the same. As we will see, when ω and C are changed, meaning different n and e values at the same specific energy, pulp properties change considerably.

Rotational speed

For the non-pump-through refining systems we considered, at a given specific energy E an increase in

rotational speed ω increased e and decreased n . This is shown in Fig. 2, where the calculations have included two additional speeds of 1500 and 2400 rpm. At a given ω , doubling the specific energy from 4.26 to 8.52 GJ/ton decreased e by approximately 23% and increased n by about 160%. In absolute terms, however, e changed more and n changed less at higher than at lower rotational speeds. A similar plot was obtained when the residence time was plotted against the specific refining power e' according to Eq. 6.

Figure 2 suggests that with increased specific energy, the proper-

ties of fibers may have developed in different ways when pulp was refined at various rotational speeds. Both the rate and the magnitude of the changes in pulp properties may be different for a given change in E as a result of the change in slope with rotational speed.

Indeed, this contention is borne out by the experimental results shown in Fig. 3. Somerville shive, freeness, and long fiber content decreased faster with increased specific energy at 1800 than at 1200 rpm. Fines generation was higher at 1800 rpm (8), with concomitant effects on sheet density, which was higher than the corresponding values at 1200 rpm (Fig. 4).

Other properties such as breaking length and tearing resistance depend on both fiber length and fiber specific surface area and are determined by the relative values of these two pulp properties. Because of the considerable reduction in fiber length at 1800 rpm, as shown in Fig. 3, both tensile and tear strengths were lower at 1800 than at 1200 rpm (Fig. 5).

These results on the effect of rotational speed on the properties of mechanical pulps are in accordance with those reported earlier (2, 10).

Wood species

Differences in fiber morphology will affect the development of fiber properties during refining. The equations do not contain any parameter for fiber properties and therefore cannot account for the observed differences in the quality of the pulps made from different species. The effect of species on residence time may be expressed through the steam flow term (which has been neglected in this analysis). This term can change in response to the differences in the compressibility of the pulp pad (1). Fiber morphology can also affect the values of the friction coefficients μ_r and μ_i in Eq. 1. When n and e (and therefore E) are constant, fibers of different morphology will not respond in the same manner to the applied energy. A higher value of n or e or both will be required to impart the same degree of flexibility as the thickness of the fiber wall increases.

A measure of the response of fibers to refining can be obtained by plotting the pulp properties against specific energy. When machine and operating parameters are kept constant, the higher the slope of the line, the greater

the effect of refining. In Fig. 3 are examples of such plots, and Table II shows the values of the slopes for a number of physical properties. A negative value shows a decrease with specific energy, whereas a positive value shows an increase in the property value. The lower the slope, the slower the property develops. Figure 3 and Table II show that at a given ω , freeness, shive, and long fiber content developed at the same rate for cedar and pine TMP. Other properties, however, changed at a different rate, and the effect of ω on the slope varied with the property under consideration: the slope increased, decreased, or remained the same.

Pine developed strength more slowly than did cedar (Table II). Since the decrease in freeness and L-factor were the same (Fig. 3), the differences in tensile strength and tear strength (Fig. 5) were due partly to the stiffer and less conformable pine fibers, as indicated by its lower sheet density (Fig. 4). In addition, there are fewer fibers in the loblolly pulp sheet than in the cedar pulp sheet because of the difference in fiber morphology and coarseness, and this affects handsheet properties (11). Refining conditions can be manipulated, however, to produce from the two species pulps that are similar, if not identical.

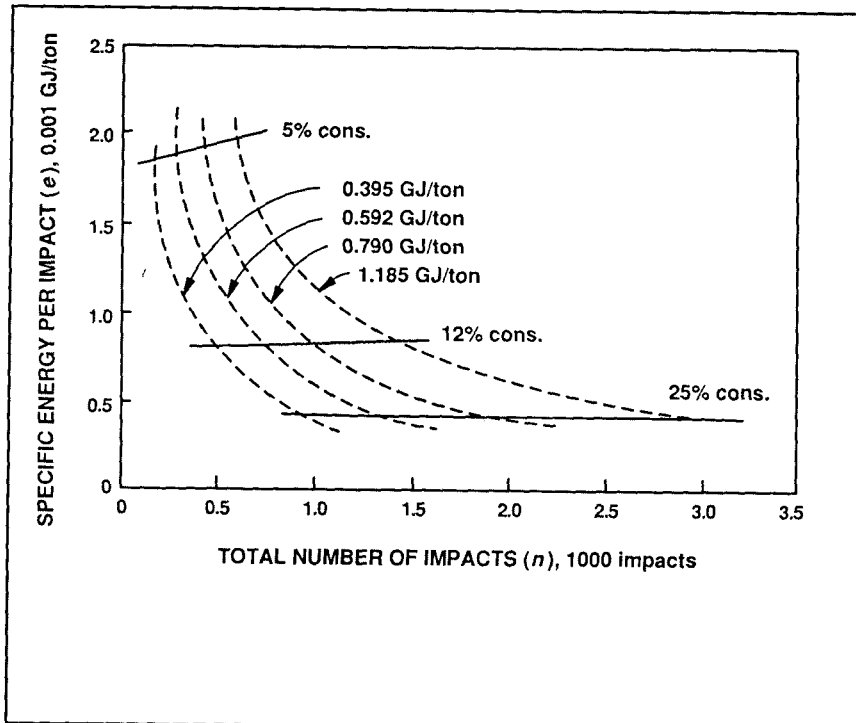
Pine is a stiffer fiber than cedar. To impart the same degree of flexibility, the residence time in the refiner should be increased, which in turn increases n . Residence time can be increased by decreasing ω or increasing consistency, or both. Table III presents a comparison of two TMP pulps, one made from cedar at 7.8 GJ/ton and 1800 rpm, the other from pine at 11.3 GJ/ton and 1200 rpm. Pine requires more energy than cedar to develop its properties, but it may be possible to minimize energy usage by optimizing the process in terms of n and e . The determination of the optimum n and e for the various wood species will require further experimental and theoretical work.

Chemical pulps

Experimental procedures

Chemical pulps were also refined at the Sprout-Bauer Laboratory, using in this case a Bauer 1016-mm-diameter (40-in.), double-disc refiner operating at 1200 rpm. Pulps were

6. Variations in e and n with consistency and specific energy. Increasing C at constant E decreased e and increased n . However, increasing E at constant C increased n , but e remained constant. The solid lines are the iso-consistency lines, and the broken lines are the iso-energy lines.



refined in a single pass (12). Prior to refining, the samples were thickened to 25% consistency and were diluted as required to 12% or 5% by adjusting the dilution water flow. The properties of the pulps after thickening were taken to be the properties of unrefined pulps because of the fines lost during thickening. [More details of the experimental procedure are given elsewhere (13).]

Pulp and handsheet testing was done according to CPPA procedures. Commercial dried pulp samples of semibleached sulfate and low-yield sulfite pulps produced from Eastern Canadian softwood species (mostly spruce) were used in the experiments.

Refining consistency

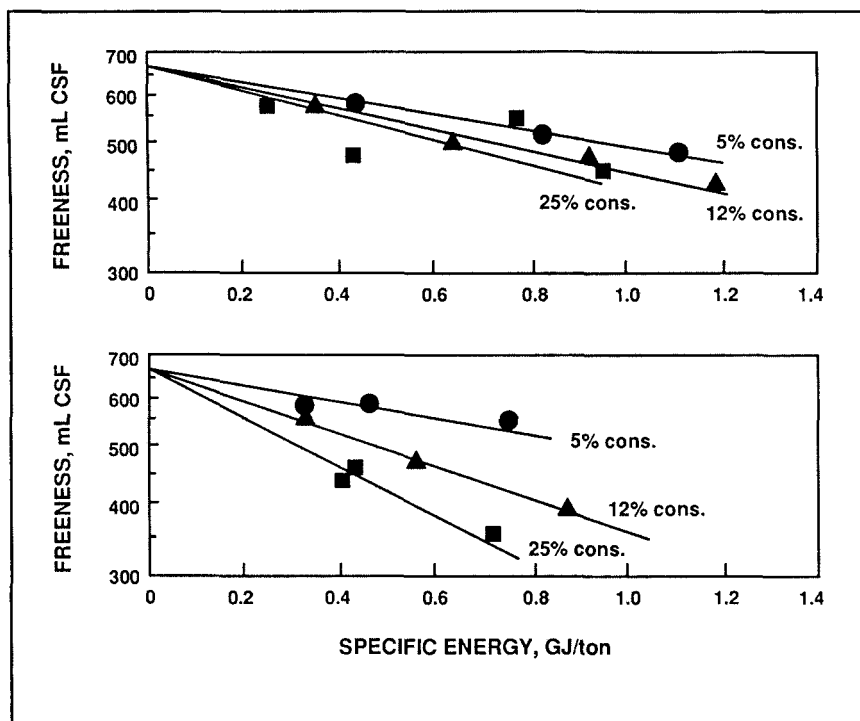
The effect of consistency on residence time, plate clearance, and pulp quality in high-consistency chip refining has been described previously (1, 2, 14). The effect of refining consistency on the properties of bleached hardwood and softwood kraft pulps has also been discussed recently (13). The theoretical equations show that, for an open discharge refiner, an increase in consistency at constant specific energy results in a longer residence time because of the reduction in wet

mass and a decrease in available centrifugal force. In our study, the longer residence time increased n and decreased e (Fig. 6). Note that at a given consistency, an increase in E increased n , but e remained essentially unchanged (Fig. 6).

Previous work has shown that the energy required to reach a specific freeness decreases as the refining consistency increases (13). This finding is also borne out by the data shown in Fig. 7 for the two chemical pulps used. Sulfite pulp responded better to medium-consistency and high-consistency refining than did sulfate pulps. The response of semibleached kraft pulp was similar to that of bleached kraft (13). Hardwood bleached kraft responded better than softwood kraft to high-consistency refining (13).

The higher rate of decrease in freeness with specific energy during high-consistency refining is due to the gentler refining (higher n and lower e) brought about by an increase in consistency. This gentler refining improves fiber development, which, in the absence of noticeable fiber shortening and fines generation, results in lower freeness with high-consistency refining than with low-

7. An increase in consistency C decreased the specific energy required to obtain a given freeness.



consistency refining. Better fiber development gave higher tensile strength to the pulps treated by the high-consistency refining process than to those treated by the low-consistency refining (Fig. 8). However, the improvement also resulted in a lower scattering coefficient at a given tensile strength (Fig. 9). The tear-tensile strength relationship was quite similar for high-consistency refining and low-consistency refining pulps (Fig. 10). This result suggests that equivalent strength can be obtained from high-consistency refining if the energy consumption is lower.

Discussion

The experimental results were obtained with pulps made from different wood species of various yields. All refining was carried out in open discharge disc refiners. The size of the refining equipment was not a variable in these experiments because the disc diameter was constant in the mechanical pulping (914.4 mm) and stock refining (1016 mm) experiments. Regardless of how energy was applied, refining consistency and rotational speed varied considerably.

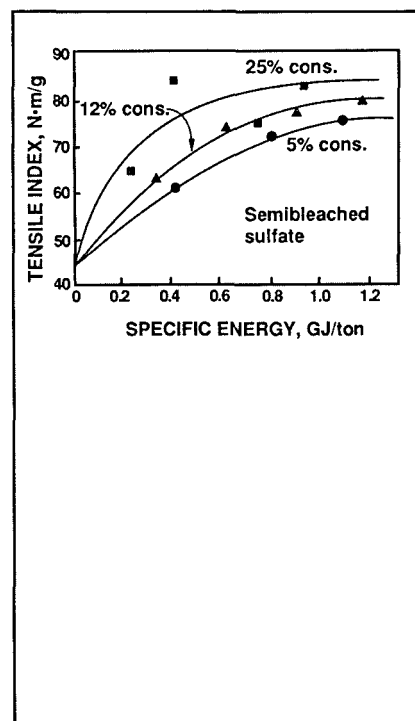
Figure 11 shows the range of n and

e employed in the experiments. Mechanical pulps were refined in a range of low e but high n . The low value of e was a result of the high consistency normally used in chip refining. Refining of chemical pulps, normally done at about 5% consistency, was in the range of low n and high e . The high-consistency refining of chemical pulps was carried out at both low n and e .

The effects of decreasing ω and increasing C were similar in the sense that both changes decreased e and increased n . If the same values of n and e are reached, would it matter whether the values were brought about by a change in ω or C . It has not been determined whether either would have the same effect on the energy-quality relationship of different types of pulps.

An increase in e is expected to be associated with more fiber shortening. This association was demonstrated at high values of E : for mechanical pulps, ω was increased, and more fines were produced. When the specific energy E is low, as for chemical pulps, increasing e by decreasing C did not result in substantial fiber cutting (13), but the development of fiber properties was slower. As a result, freeness decreased with mechanical pulps but

8. Tensile index increased with increasing specific energy E and at a given E was greater at a higher refining consistency.



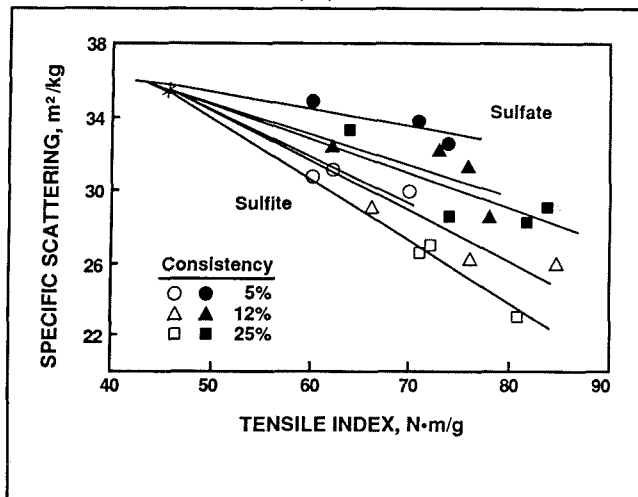
increased with increasing e with chemical pulps. However, strength properties improved as n increased and e decreased for both chemical and mechanical pulps. More work is needed to establish the effect of yield and specific energy level on the response of pulp fibers to refining.

Conclusions

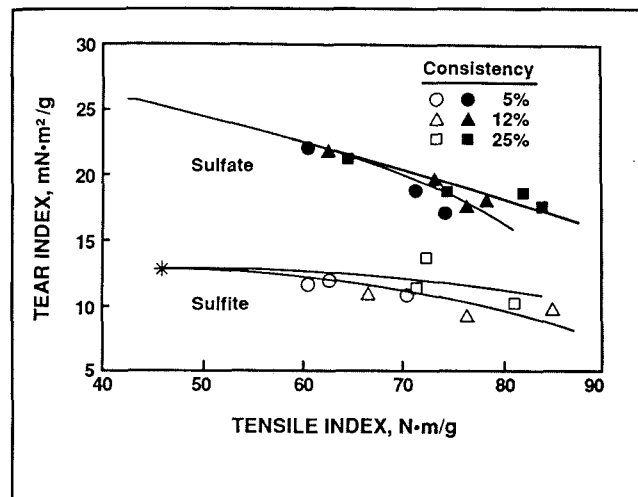
A number of specific conclusions may be drawn:

1. If the refining variables have been properly adjusted to the same values of E , n , and e , the quality of mechanical pulp is independent of the number of refining stages, or the number of passes.
2. At a given specific energy E , increasing the number of impacts n and decreasing the specific energy per impact e results in stronger pulps. This finding holds for both chemical and mechanical pulps.
3. Increasing e in mechanical pulps by increasing rotational speed ω at constant E , increases the rate of fines generation and results in a faster drop in freeness.

9. At a given tensile, the scattering coefficient was reduced as the refining consistency increased. The scattering coefficient was also lower for sulfite than for sulfate pulp.



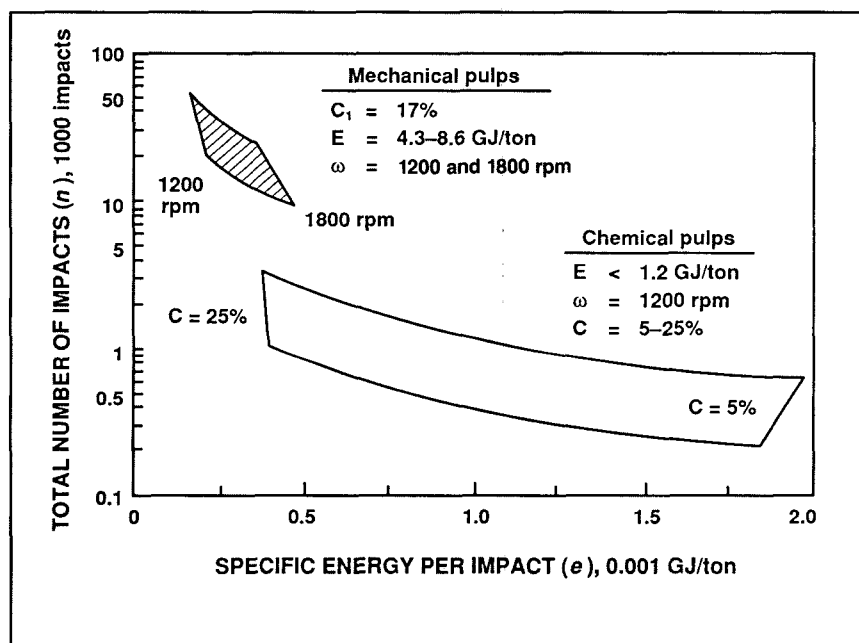
10. The tear-tensile strength relationship of chemical pulps was relatively independent of refining consistency.



4. Chemical pulps are refined at much lower E , and an increase in e achieved by decreasing consistency C does not cause any appreciable fiber shortening. Fiber development and freeness decrease in chemical pulps appear to be slower for low-consistency refining than for high-consistency refining.

The theoretical and experimental work described in this and in previous reports indicates that the papermaker has available a number of variables by which to manipulate the quality of the product: specific energy, consistency, rotational speed, and plate design. These variables can be adjusted to produce pulp from different raw materials but with properties suitable to meet the product requirements. Moreover, a qualitative knowledge of the effect of these variables on pulp properties will result in an improved and more uniform quality through better control of the refining process. □

11. The ranges of the refining operating variables for the mechanical and chemical pulps.



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