Characterizing refining action in PFI mills

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ABSTRACT: The PFI mill continues to be the most commonly used laboratory refining device, despite much evidence that its refining effect differs from disc and conical refiners. The potential causes of this difference are evident in its unique geometry, high consistency, and mode of operation. But precisely how do these differences affect its refining action relative to industrial refiners? This study has examined the features of the PFI mill that affect its refining action and compared these to those of a laboratory conical refiner in terms of refining energy, refining intensity, and other factors governing action on pulp. Comparisons were also made of pulp property changes at equivalent values of energy and refining intensity and to theoretical values of refining intensity and energy.

Compared to the conical refiner, the PFI mill is a very low intensity and high energy refining device. This accounts in part for differences between the refiners in normal operation, but even at the same energy and intensity, the PFI was found to produce a differing refining effect, namely a smaller reduction in freeness and an increase in tensile strength. This suggests that the PFI action is mainly one of causing internal fibrillation, a finding in agreement with conclusions of earlier authors. Comparisons of the magnitude of the PFI mill intensity with intensities estimated from earlier work on a roller device and theoretical predictions are consistent with cyclic compression and internal fibrillation.

Application: This study compares the PFI mill to industrial refiners in terms of specific energy and refining intensity and identifies some of the key reasons for the differences. Mills can benefit from this work in knowing the true magnitude of the difference between the PFI mill and their industrial refiners.

PFI mills remain the most widely used laboratory refiners in use today. In an earlier paper [1], we reviewed past studies of this device and presented an approach to quantify its refining action in terms of specific energy and refining intensity. In this paper, we expand upon these findings and other recent studies to provide some new perspectives on our understanding of the refining process.

QUANTIFYING REFINING ACTION

Specific energy

Specific energy is the most easily measured quantitative characterization of refining action, but surprisingly, it is seldom measured in the PFI mill. Instead, the extent of refining is described by the number of revolutions. Nevertheless, various researchers have published measurements of energy for the mill [2-5] which have been summarized [1]. These data are reproduced in **Table I**.

It is apparent that differing pulps can have differing energy values, but the average value is approximately that for bleached softwood kraft (BSK) pulp—about 0.63 J/g/rev. This can be expressed more conveniently as:

$$E = \frac{0.18\ kWh}{metric\ ton\ -\ revolution}$$

From this expression, we may note that 6000 revolutions correspond to a specific energy of approximately 1000 kWh/metric ton. More recent measurements [6, 7] give energy values in the same range as these earlier studies. This is 10 times the energy typically used in industrial refiners. Thus, the PFI mill is a high-energy refiner.

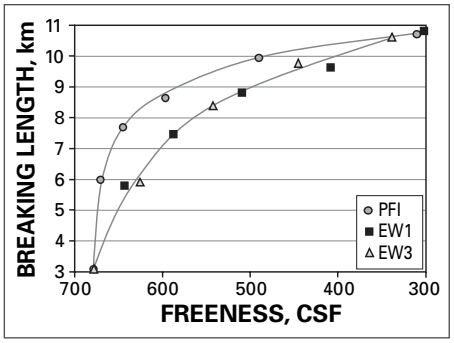
In measuring energy, the question of *no-load power* must be addressed. A scientifically rigorous definition of no-load power is the power expended on pulp flowing through the refiner which does not cause measurable change in the pulp. In low consistency refining, this can readily be measured by the power with plates backed off. However, vanes acting on pulp at medium consistency (10%), even in the case of a very wide gap, create a refining effect (as in medium consistency fluidizers and pumps) [8]. Indeed, the action may be opposite to that expected for a loaded gap. For example, pulp may be curled [4], whereas under typical PFI operation it is straightened. Thus, no-load with pulp in the PFI mill is not likely to be meaningful. Therefore, in this study we have measured no-load in the absence of pulp [1]. The agreement in energy values between this and other studies suggests that the latter were measured similarly.

Refining intensity

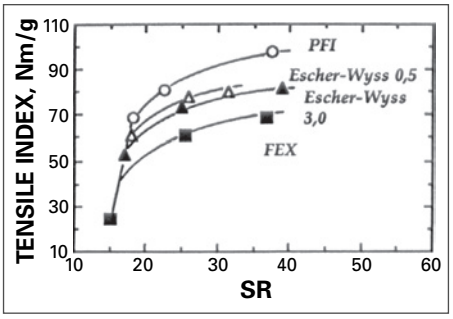
The geometry of the PFI mill makes it difficult to estimate refining intensity. Pulp at 10% consistency is held on the outer rotating housing by centrifugal forces and passed cyclically through a "working zone" in which bars from a rotor engage the pulp. The bars move at a relative velocity of approximately 6 m/s to the housing.

The size of the working zone is uncertain. Accordingly, in our earlier work [1], we estimated an upper and lower limit of this size. The upper limit was defined as a zone in which some bar contact took place with the pulp pad whereas the lower limit was defined as a zone extending over an arc of three rotor bars.

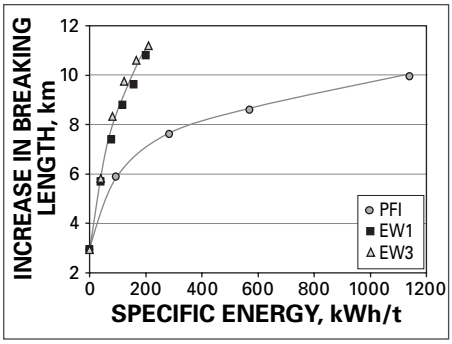
Using these estimates, and an approach based on the "C factor" intensity imparted to fibers during refining [1], we estimated refining intensity as the energy expended on a fiber during one impact, that is, during one straining cycle imposed by a passing bar. The intensity can be expressed as a specific energy per impact, which we call "specific intensity," *S*. For BSK, the estimated values of *S* in the PFI mill were 0.25 kJ/kg/impact for the large zone and 2.5 kJ/kg/impact for the small zone. Given the uncertainties in this estimate, it is reasonable to use an approximate value of S = 1 kJ/kg/impact as a representative value.



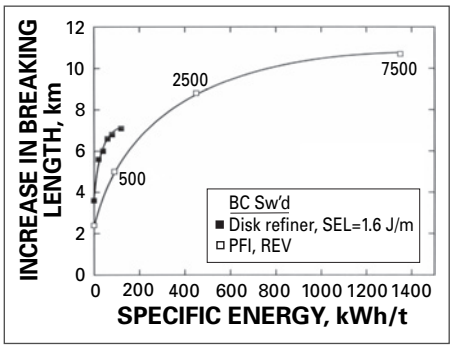
1. The PFI mill producers higher tensile strength at a given freeness than the Escher-Wyss (EW) lab refiner at SEL = 1 and 3 J/m.



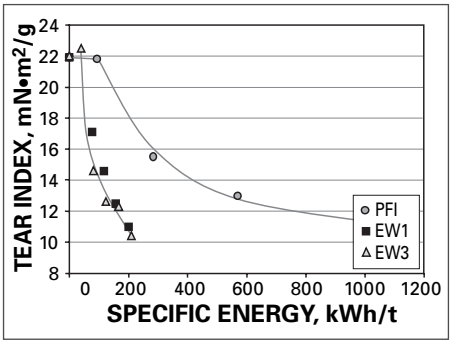
2. Comparison of tensile strengths at a given freeness for the PFI mill, the Escher-Wyss lab refiner, and an industrial refiner (Mohlin [14]). The values 0.5 and 3.0 refer to SEL in J/m.



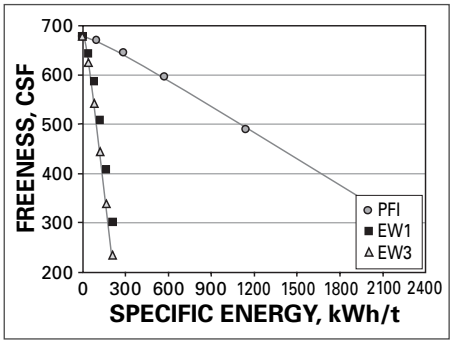
3. The Escher-Wyss refiner at SEL=1 and 3 J/m produces a higher tensile strength than the PFI mill at equal specific energy.



4. An industrial disc refiner produces greater tensile strength than a PFI mill at equal specific energy.



5. The EW refiner at SEL=1 and 3 J/m produces a much greater decrease in tear strength than the PFI mill at equal specific energy.



6. The EW refiner at SEL=1 and 3 J/m produces a much greater decrease in freeness that does the PFI mill at equal energy.

Reference	Pulp Type	SPECIFIC ENERGY/REVOLUTION J / g - rev	SPECIFIC ENERGY/REVOLUTION kwh / metric ton - rev
McKenzie [2]	Eucalypt kraft*		
	5000 rev	0.54	0.15
	3000 rev	0.55	0.15
	pine kraft		
	5000 rev	0.80	0.22
Phillips, Bain, and Watson [3]	Unbleached eucalypt		
	kraft #1	0.66	0.18
	kraft #2	0.55	0.15
Hatton [4]	Unbleached		
	Softwood kraft	0.72	0.20
Welch and Kerekes [1]	Bleached		
	Softwood kraft	0.59-0.68	0.16-0.19
	Unbleached		
	Softwood kraft	0.69-0.72	0.19-0.20
Polan [5]	Bleached		
	Softwood kraft (mixed species)	0.61-0.64	0.17-0.18

* bleaching conditions not stated.

I. Energy consumption in PFI refining.

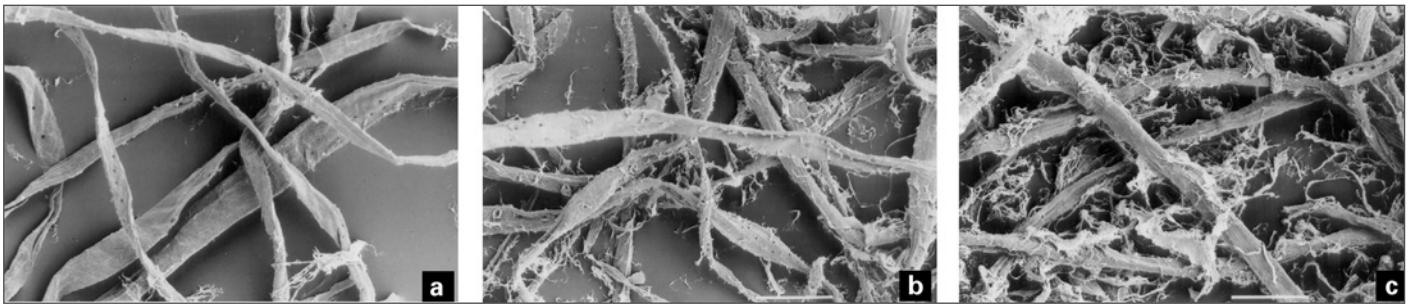
This value is considerably less than the range found in industrial refiners, which are 10–50 kJ/kg/impact [9]. Similarly, it is less than values corresponding to "best practice" specific edge loads recommended by Baker [10], which are 0.2 J/m for hardwoods and 2.0 J/m for softwoods, which correspond to 11 kJ/kg/impact and 16 kJ/kg/impact, respectively [11].

In summary, the refining intensity in the PFI mill is approximately one-tenth of that of industrial refiners. It is a very low intensity refiner.

COMPARISONS OF PULP PROPERTIES

Laboratory conical refiner

We now compare pulp properties produced by the PFI mill with those produced in a laboratory conical refiner which simulates an industrial refiner—the Escher-Wyss laboratory refiner (EW). This refiner produces pulp properties similar to those of mill refiners at equal



7. The EW creates more external fibrillation and fines than the PFI mill: a) unrefined pulp; b) PFI 6000 rev; c) EW 240 kWh/metric ton, SEL = 3 J/m (Polan [5]).

Refining	Freeness CSF mL	SPECIFIC SURFACE Whole Pulp m^2/g	SPECIFIC SURFACE R14 and R28 fractions m^2/g
Unrefined	718	1.44	1.02
PFI (6000 rev)	366	5.37	1.41
EW (240 kWh/metric ton, SEL = 3 J/m)	117	10.5	1.14

II. Hydrodynamic specific surface [5].

specific energy and intensity for high-intensity refining [12]. However, Mohlin [13] found that the EW produced greater water retention values than an industrial refiner at the same energy and specific edge load. Factors such as the multiple pass mode of operation of the EW refiner may account for a difference. Nevertheless, it is clear that the EW refiner simulates industrial conical and disc refiners more closely than does the PFI mill.

PFI vs. Escher-Wyss refiner comparisons

Here we compare the refining effect of the PFI and EW refiners on an interior British Columbia bleached softwood kraft pulp (BSK). First we consider a paired property comparison—tensile strength at a given freeness (**Figure 1**). The PFI mill here shows superior strength development at a given freeness, as found by others, such as Mohlin [14] in the data shown in **Fig. 2**.

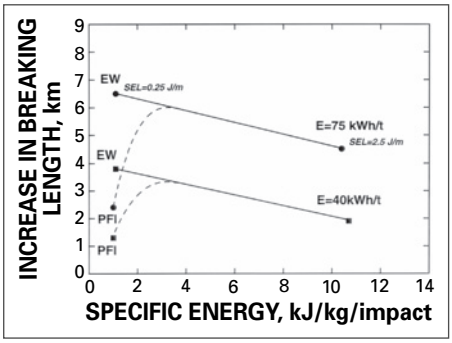
However, the findings are reversed when compared at equal energy. As shown in **Fig. 3**, at a common specific energy, the EW produces a significantly higher strength than the PFI mill. This finding also holds true for industrial refiners (**Fig. 4**). Tear strengths after EW refining decrease to a far greater degree at equal energy (**Fig. 5**).

The differences between these freeness-based and energy-based comparisons are explained in part by the significantly larger freeness change produced by the EW refiner at a given energy. This is evident in **Fig. 6**. The freeness decrease comes largely from external fibrillation and fines, evident in photomicrographs (**Fig. 7**) for a similarly refined pulp by Polan [5]. The hydrodynamic specific surfaces of these pulps are given in **Table II**. The lower freeness produced by the EW refiner is reflected in two times the external specific surface produced by a PFI mill. Interestingly, the specific surface of the long fiber fractions of the two pulps differ little. This suggests that the external fibrils are weakly held on the fibers and turn into fines during passage through the classifier.

COMPARISONS AT EQUAL ENERGY AND INTENSITY

We next address the question of whether these observed differences may be explained solely by the differing level of intensity in the two devices. To determine this, experiments were conducted by lowering the power level of the EW refiner to approach the intensity in a PFI mill. **Figure 8** shows the results.

It is apparent that even at equal intensity and energy, the EW refiner produces a greater increase in tensile strength than does the PFI mill. Thus, there are differences in the mechanics of refining between the two devices which cannot be explained by energy and intensity alone.



8. At equal specific energy and specific intensity, the EW refiner produces a greater increase in tensile strength than does the PFI mill.

COMPARISONS OF COMPRESSION AND SHEAR IN REFINING

We did not analyze in detail the refining mechanics of a PFI mill for this report. However, some useful insights may be gained by comparisons with other experimental findings and theoretical predictions.

Previous researchers have modified the PFI mill in various ways. In one study, Bovin [15] placed bars on the outer housing, which produced a refining result much closer to industrial refiners. In another study, Murphy [16] reduced the relative velocity between the rotor and bed plate from 6 m/s to 0. While this diminished the effectiveness of the PFI mill, its refining effect nevertheless remained significant. In another experiment, he rounded off the edges of the rotor bars at the standard operating condition of 6 m/s relative velocity. This was found to have little effect on the refining result.

More recently, Lossada et al. [6] have performed similar experiments in the PFI mill at 6 m/s and 0 m/s relative velocity, as have Formento et al. [7].

They found that the pure compression mode (0 m/s) produced the level of tensile strength attained in the standard mode (6 m/s), at less energy and freeness loss, but longer refining time.

These changes in PFI operation increase the proportion of compressive force to shear force on fibers. The findings support the conclusion of Watson and Phillips [17] that the beating effect of the PFI mill is largely determined by the rapid application of compressive forces upon the pulp. In more recent work, Dekker [18] also concluded that fiber compression was a key target of refining.

Further evidence of this is available in comparisons with a Lampen mill, as reported by Murphy [16]. In this device, a 10 kg ball rolls over pulp as the mill is rotated. Its action is clearly largely one of cyclic compression of the pulp. Using the PFI mill with 9 kg loading, and zero relative velocity between the rotor and housing, Murphy found that it produced nearly the same effect on eucalypt pulp as did the Lampen mill.

Additional evidence of the role of compression can be found in the novel experimental work of Hartman [19]. He treated pulp by repeated passage of a rotating roll over a pulp pad. This produced a significant refining effect (primarily internal fibrillation). Few fines and little external fibrillation or fiber shortening were created. Nevertheless, the roller produced an increase in tensile strength at 40 kWh/metric ton, equivalent to that of an EW refiner at 300 kWh/metric ton at low intensity and 160 kWh/metric ton at high intensity [19]. However, the roller reached a plateau at this level, whereas EW continued to increase in strength with further refining.

The refining effect of this roller device was attributed to cyclic compression. Interestingly, its refining intensity estimated from measurements reported by Hartmann [19] is approximately 0.4 kJ/kg/impact. This is at the lower end of the estimated range of the PFI mill.

In another unique experiment, Martinez [20] measured forces on fiber flocs sheared by crossing bars in a single-bar refiner device. The level found was S = 20 kJ/kg/impact, the approximate level of industrial refiners. Martinez [21] also showed this energy to be six orders of magnitude greater than the energies required to bend fibers by hydrodynamic forces.

In summary, the refiner intensity found in a cyclic compression device corresponds to the level in a PFI mill, whereas the intensity found in a shearing device corresponds to intensities found in industrial refiners. These estimates support the concept that the PFI imposes a high ratio of compressive to shear forces in comparison to industrial refiners.

Homogeneity of treatment

It is well known that industrial refiners give heterogeneous treatment of pulp whereas the PFI treatment is much more uniform [22]. Heterogeneity may be of differing scales, from macroscale non-uniform flow patterns within a refiner, to microscale non-uniformities in force distribution within a single floc. The extent of the latter has been demonstrated in recent work [23]. To overcome non-uniform distribution of forces among fibers in a network, Steenberg [24] pointed out years ago that fiber networks must be redistributed periodically to expose new fibers to loading. This is a part of refining, but how much redistribution is needed? This question assumes importance because network redistribution consumes energy.

Network redistribution plays a role in the difference between Hartman's roller device and PFI mills. The roller, having no network redistribution at all, quickly reaches a plateau of effectiveness at 40 kWh/metric ton. However, within this range it is very efficient, producing a much greater tensile strength increase than the EW refiner, whereas the PFI produces much less of an increase. Because the refining intensities of the PFI and roller device are nearly similar, we may ask why the PFI consumes so much more energy for apparently less effect. The answer may lie in network redistribution, which is extensive in the PFI. Experiments have shown that it mixes pulp very rapidly and very well [25]. Microscale mixing of pulp at 10% consistency consumes considerable energy [26]. If the network redistribution is more than necessary for uniform refining, there may be an unnecessary expenditure of energy in this device.

COMPARISONS WITH THEORETICAL ENERGIES

We now address the question of how much energy is needed to refine fibers from a theoretical standpoint. While our present level of understanding does not permit a detailed analysis of refining action, we may use estimates of refining energies to shed some light on the mechanics of the process.

Van den Akker provided one of the earliest estimates of theoretical energy required for refining [18]. He estimated the following:

- for external fibrillation of 1 m^2/g: 0.035 kJ/kg
- for internal fibrillation of 90 m^2/g: 1.4 kJ/kg
- for fiber cutting: 0.0001 kJ/kg

It is evident here that most of the energy is required for internal fibrillation. The energy for this—1.4 kJ/kg—corresponds to 0.4 kWh/metric ton, which is about one-thousandth of the energy used in industrial refining, assuming the latter to be 400 kWh/metric ton [27]. This comparison is the basis of the often quoted statement that pulp refining is an extremely inefficient process, having only 0.1% efficiency.

Surprisingly, this energy level is close to that of a single strain cycle in the PFI mill and Hartman's apparatus, both of which produce primarily internal fibrillation. This may be coincidence, but there may be a physical explanation.

Taking another approach, Nissan [28] estimated a theoretical energy of refining by considering how the refining effect was created. He estimated the energy necessary to strain a fiber by 3% in tension, considering this level of strain to be sufficient to induce some permanent deformation (the refining effect) without breaking the fiber. This gave an estimate of about 8 kJ/kg/impact [6]. This is at the lower end of the range used in industrial refiners [6] and about five times Van den Akker's estimate.

Nissan's estimate is based on imposing strain upon fibers. All or most of a fiber must be strained to a high level to attain new surface in some part of it. Some of the energy expended in this process is recovered elastically by the fiber, but for all practical purposes, it is lost to the external source of the

refining. It is a necessary consequence of creating new surface through strain imposed by an external force.

These observations suggest that Van den Akker's estimates may apply to a single straining cycle rather than the entire refining process. Just as Nissan's estimate is close to measured values of a single strain cycle imposed by shear during a bar crossing, so Van den Akker's estimate is close to a single strain cycle imposed by compression in the PFI and roller device.

This conclusion is speculative at present. However, if it is correct, we can only agree with Nissan [28] that: "Refining is not the pathetically inefficient process assumed for decades by authorities wringing their hands at figures of 0.1% or less. I believe it is a fairly efficient process, a fact which adds to its fascinating character."

SUMMARY AND CONCLUSIONS

The PFI mill is a high energy, very low intensity refining device. However, even at the same energy and intensity as an Escher-Wyss laboratory refiner, the PFI produces a refining effect that differs significantly from this refiner. Thus, while the PFI mill is useful for laboratory comparisons, it is not a good predictor of industrial refining.

The finding of this study and earlier studies suggest that the PFI mill imposes a greater proportion of compressive to shear forces than does an industrial refiner, and that this action is responsible for the higher internal fibrillation and lower external fibrillation and fiber shortening.

Comparisons to theoretical predictions of refining energy suggest that the refining may not be as intrinsically inefficient as once thought. Further research on this fundamental aspect of refining is much needed. **TJ**

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INSIGHTS FROM THE AUTHOR

We chose this research because the PFI mill is the most widely used laboratory pulp refining device in the industry and has long been known to produce results that differ from industrial refiners. However, the reasons why have not been clear.

Several years ago, we developed the C Factor to describe refining intensity in disc and conical refiners in terms of energy imparted to fibers by bar crossings. This approach also permits comparison with the PFI mill. The most difficult aspect of the work was estimating the number of bar impacts that fibers are likely to experience in the PFI mill. The difficulty stems from the unique geometry of the device and the fact that it operates at 10% consistency.

Perhaps the most surprising result of the research was that, even at the same intensity and energy, the PFI mill produced substantially different results from a conical refiner. We had thought that its action might be largely explained by its very low intensity.

Mills can benefit from this work in knowing the true magnitude of the difference between the PFI mill and their industrial refiners. In some cases, its very low intensity may give misleading results, as in the case of fibers especially susceptible to damage or rupture.

Our work on characterizing refining actions continues. The objective is to overcome the shortcomings of energy-based methods for quantifying refining action used in this work and generally. Our new approach is based on forces acting in fibers in addition to energy expended.

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