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REFINING IMPULSE CONTROLS THE MORPHOLOGICAL MODIFICATIONS OF FIBERS

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ABSTRACT

Considering the analogy between the pressing of a paper sheet and the refining of a pulp suspension, the *refining impulse* is introduced. For beaters, disc or conical refiners, whatever the running mode (continuous or batch), the *refining impulse* is found to be a controlling variable for the pulp properties, and consequently for the paper properties. In a Valley beater, different normal forces were applied. The SR evolution versus the *refining impulse* exhibits a unique curve whatever the experimental conditions. For disc and conical refiners, the refining impulse depends on the net power, the rotation speed, the bar width, or the average bar angle. A unique parameter is used to fit each set of trials to obtain a single curve of the SR evolution. This parameter corresponds to the global *friction coefficient f*. The fiber length and the swelling (WRV) depend also on the refining impulse. However, as in pressing theories, the applied pressure has also to be introduced as a complementary parameter. Consequently, the paper properties are shown to depend also on both the refining impulse and the applied pressure.

INTRODUCTION

Our research on refining process is motivated by (i) the control of the pulp properties and the developed paper properties, and (ii) the reduction of the specific energy consumption. The previous approaches found in the literature put the emphasis on the net tangential force, such as the net specific energy or the refining intensity, calculated from the net power or the net tangential force ([1], [2]). The importance of the net normal force is less considered [3]. We proved however that the net normal force in refiners controls, for example, the shortening effect on fibers [4]. Our major hypothesis is based on the analogy between the pressing process and the refining process: the normal stress (pressure) is mainly responsible for the modifications of the fibers. As the pressing process is mainly characterized by the pressing impulse introduced by Wahlstrom [5], we similarly define the refining impulse.

In a refiner, the net normal force is applied on fibers during the residence time of the pulp in the bar contact areas. We consider the impulse of the local mechanical pressure. We propose in this article first to define the refining impulse whatever the technology of refiner is, then, to analyze Schopper-Riegler (SR) evolution against this refining impulse for (i) a Valley beater, (ii) a disc, and (iii) a conical refiner.

In the case of bleached softwood Kraft pulps, we analyze the evolutions of SR against the refining impulse modifying engineering parameters such as the net power, the rotation speed, the bar width, or the average bar crossing angle. Finally, we prove whatever the considered technology that (i) both the fiber length and the swelling (WRV), and (ii) the paper properties, depend on the refining impulse, completed by the normal stress as a complementary parameter, similarly to the pressing theory.

METHODS

The kinetics of the SR, the Water Retention Value (WRV), and the Fiber length (L_f) are often used to control beating operations. We modified these properties on different beaters and identified some controlling parameters.

Existing approach

For a bleached softwood Kraft pulp, in a Valley beater, different kinetics of the SR degree are obtained applying different masses, from 3.5 kg to 6.5 kg (Figure 1). A mass leads to a given normal force applied in the gap clearance between the roll and the bed plate of the beater, increasing the pulp SR degree [6].

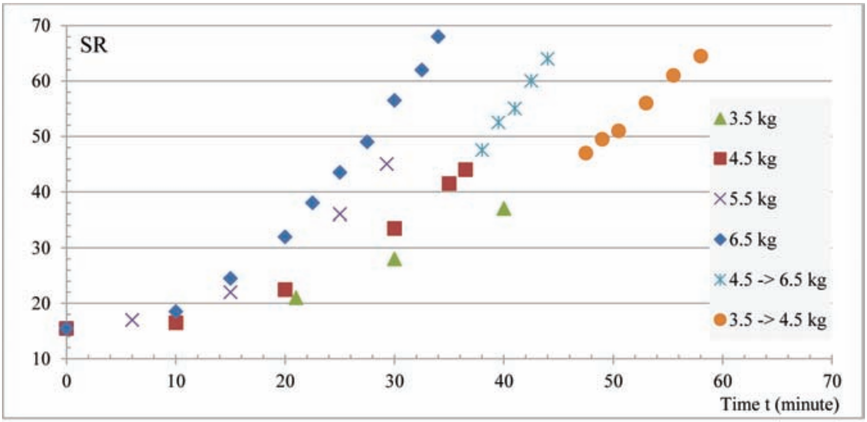

Figure 1. SR vs time – Valley beater – Bleached softwood Kraft pulp.

The higher the normal force is, the faster the evolution of the SR degree. The situation where two refiners are associated in a serial connection may be addressed changing the mass during the trials, as for example from 4.5 (or 3.5) kg to 6.5 (or 4.5) kg in Figure 1.

Classically, the SR evolution is characterized considering the net energy, E_m, per dry mass of pulp (also named Specific Energy Consumption) defined for continuous and batch running modes as:

$$E_m = n_c.e_m = n_c.\frac{P_{net}}{\dot{M}} \tag{1}$$

where n_c represents the number of cycles, e_m the net energy per dry mass per cycle, $\dot{M}$ the dry mass flux, and P_{net} the net power consumed.

In case of continuous running modes, the dry mass flux $\dot{M}$ passes only once through the refiner, hence, n_c is equal to 1.

In batch running modes, the number of cycles is given by $n_c = \frac{t}{\overline{T}_c}$ where t represents the time, and $\overline{T}_c$ is the average period of a cycle. Considering a pulp suspension pumped from a tank where the pulp suspension volume is V, the volume of the pipes filled by pulp suspension in the closed loop is v and the volumetric flow Q is measured, the average time of a cycle is then given by:

$$\overline{T}_c = \frac{V+v}{Q} \tag{2}$$

As the small volume v is often negligible compared to the volume of the suspension in the tank V, an approximation of the average time of a cycle may be given by:

$$\bar{T}_c \cong \frac{V}{Q} \tag{3}$$

Considering Eq. (1), P_{net} may appear as a possible controlling variable of the SR evolution.

Let consider now the dispersion of the data that we obtain when representing the SR degree evolution vs the net specific energy when either the refining conditions or the engineering parameters are modified. The cases of a disc refiner and a conical refiner are illustrated in Figures 2(a) and 2(b), respectively.

Case of a disc refiner

We consider a bleached softwood Kraft pulp in a disc refiner where both the volumetric flow and the consistency are kept constant; the refining condition such as, P_{net} and the engineering parameters, such as the bar width, *a*, the average bar crossing angle, *γ*, influence the SR degree evolution versus the net specific energy, E_m, as shown on Figure 2(a).

It is then clear that controlling the SR evolution seems a difficult problem since all the refining evolutions, characterized by the SR degrees, have different kinetics. For example different values of SR may be found for a given value of the net specific energy consumed.

Case of a conical refiner

Considering another bleached softwood Kraft pulp in a conical refiner, the refining conditions as the net power, P_{net}, and the rotation speed, *N*, are modified as the volumetric flow and the solid consistency are kept constant. The other engineering parameters as the bar width, *a*, the average crossing angle, *γ*, are also kept constant.

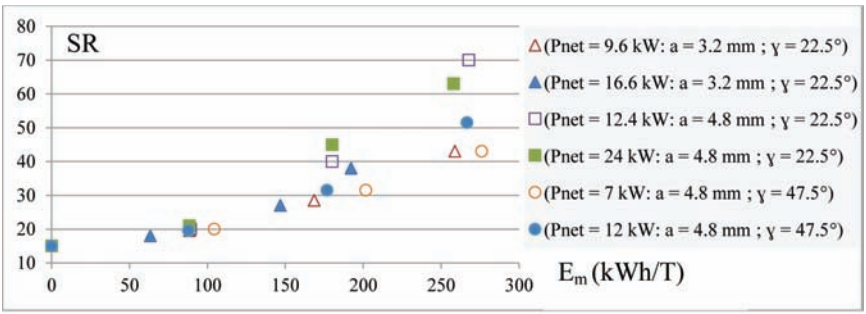

Figure 2(a). SR vs net specific energy, E_m (kWh/T) for a disc refiner and a bleached softwood Kraft pulp.

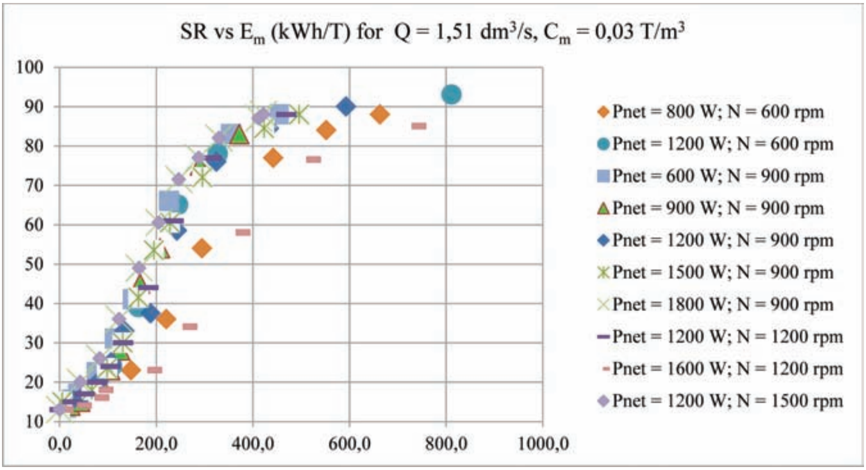

Figure 2(b). SR vs net specific energy, E_m (kWh/T) for a conical refiner and a bleached softwood Kraft pulp.

As for the case of the disc refiner, a large dispersion of the experimental data is obtained considering the SR degree evolution of the pulp vs the net specific energy for different refining conditions.

However, the curves present an S-shape. One parameter could gather all the curves whatever the refining conditions and the engineering parameters are. It is the purpose of our approach to find this fitting parameter, and identify its physical meaning.

Our approach

For wet pressing, Wahlström [5] defined the press impulse applied to the wet sheet during the nip residence time, Δt, as follows:

$$I = \int_0^{\Delta t} P_{tot}(t').dt' = \overline{P_{tot}}.\Delta t \tag{4}$$

where P_{tot} is the local total pressure in the nip, and $\overline{P_{tot}}$ the average pressure.

Wahlström demonstrated that the paper dryness after a press depends on this press impulse. When the average pressure has to be introduced as a supplementary variable, the paper furnishes exhibit a "compression controlled" case, as opposed to the "flow controlled" case.

Considering the construction of a classical pulp refiner and the disproportion between dimensions of fibers, refining bars and refining gap [9] (Figure 3), we

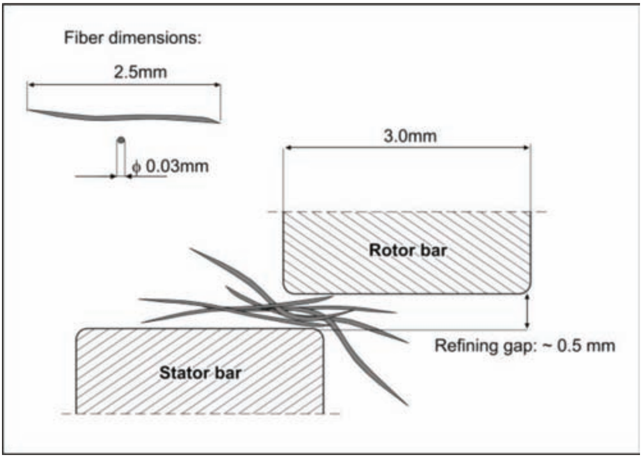

Figure 3. Characteristic dimensions of fibers, refining bars, and refining gap.

postulate that the refining effects on pulp fibers are performed by a succession of elementary presses, named mini-press. The main theoretical concepts are presented in the Annex.

One mini-press is localized in the contact area considering an average bar crossing between a rotor bar and a stator bar. In one cycle, during its average path £ through the refining zone, the pulp suspension is subjected to N_{mp} elementary mini-presses. N_{mp} is mainly a function of the geometrical parameters such as bar widths, bar grooves, or average bar crossing angle.

For one cycle, the refining impulse, I_1, is hence defined as the cumulative effect of each identical refining impulse, i_1, considering the N_{mp} elementary mini-presses:

$$I_1 = N_{mp}.\, i_1 \tag{5}$$

For n_c identical cycles, the total refining impulse applied on the pulp fibers is calculated accordingly:

$$I_T = n_c.\, I_1 = n_c.\, N_{mp}.i_1 \tag{6}$$

The elementary refining impulse applied by a mini-press, i_1, considering the local pressure $\overline{P}_1$ is defined as:

$$i_1 = \int_0^{t_{eff}} P_1(t').dt' = \overline{P}_1.t_{eff} \tag{7}$$

- The average pressure $\overline{P}_1$ is calculated for one mini-press or for the bar contact area, A_{cp}, as:

$$\overline{P}_1 = \frac{F_n^{net}}{A_{cp}} = \frac{F_n^{net}}{\overline{N_{cp}}.a_{cp}} \tag{8}$$

where a_{cp} represents an elementary bar contact area. Considering all identical bar crossings, $\overline{N_{cp}}.a_{cp}$ represents the total bar contact area A_{cp} of the overlapping zone similar to the one defined by Jagenberg [7] for beaters. The net normal force, F_n^{net}, in the gap clearance, is applied on pulp fibers considering the average number, $\overline{N_{cp}}$, of bar crossings.

- We also have to calculate the efficient time, t_{eff}. The average time cycle, $\overline{T}_c$, can be decomposed into the time out of the refiner, T_0, and the residence time inside the overlapping zone of the refiner, T_{raff}. Again, T_{raff} can further be considered for the N_{mp} mini-presses.

  For one mini-press, the time, t_{non_eff}, during bar/groove, groove/bar or groove/groove crossings is not efficient on a pulp refining point of view. The efficient time, t_{eff}, has therefore to be considered only during the overlapping of a rotor bar over a stator bar in one bar crossing. The average time cycle, $\overline{T}_c$, is hence decomposed as follows where only the last term leads to an effective refining impulse:

$$\overline{T}_c = T_0 + N_{mp}.t_{non\_eff} + N_{mp}.t_{eff} \tag{9}$$

  The efficient time t_{eff} for an elementary mini-press is calculated considering the impact length [8] and the space average tangential velocity $\overline{V}_t$:

$$t_{eff} = \frac{l_{impact}}{\overline{V}_t} \tag{10}$$

  The total refining impulse is thus calculated as follows:

$$I_T = n_c.N_{mp}.i_1 = n_c.N_{mp}.\overline{P}_1.t_{eff} \tag{11}$$

Expression of the total refining impulse, I_T, in function of the net normal force

- The number of cycles n_c was already calculated, based on the period $\overline{T}_c$.

- The number of mini-press, N_{mp}, can be determined considering the average path £ of the pulp suspension inside the refiner, divided by the average length, l_{inter}, of a mini-press:

$$N_{mp} = \frac{£}{\left\{\dfrac{\frac{1}{2}(a_r + b_r + a_s + b_s)}{cos(\gamma/2)}\right\}} \qquad (12)$$

The engineering parameters are hence explicitly introduced, as the bar crossing angle γ on the average, the bar width a, the bar groove b, with the subscripts (r) for the rotor, (s) for the stator.

- The efficient time t_{eff} is calculated considering the impact length, l_{impact}, as defined by Lumiainen [8]. This impact length depends also on the bar width, a, and the average bar crossing angle, γ:

$$t_{eff} = \frac{l_{impact}}{\overline{V}_t} = \frac{a_r + a_s}{2cos(\gamma/2).\overline{V}_t} \qquad (13)$$

- Considering now the local pressure, $\overline{P}_1$, the technology of the refiner has to be introduced. First, we need to consider the total overlapping area in the refining zone: A_T. This area has to be calculated for each technology of refiners. A unique expression relates however the bar contact area to the total overlapping area by a surface fraction, ξ, of bars over the total area:

$$A_{cp} = \frac{a_r a_s}{(a_r + b_r)(a_s + b_s)}.A_T = \xi.A_T \qquad (14)$$

The average pressure for a mini-press can therefore be expressed for different technologies of refiners as:

$$\overline{P}_1 = \frac{F_n^{net}}{A_{cp}} = \frac{F_n^{net}}{\xi.A_T} \qquad (15)$$

Before analyzing different technologies of refiners, we can gather all the expressions of the 4 variables which are involved in the total refining impulse I_T, in case of equal bar width for the rotor and the stator, and equal bar groove for the rotor and the stator:

$$I_T = n_c.\left(1 + \frac{b}{a}\right).\left\{\frac{£}{\overline{V}_t.A_T}\right\}.F_n^{net} \qquad (16)$$

For a cycle, one can obtain the duration of the path of the suspension inside the refiner zone, as the ratio of the average path, £, of the pulp suspension to the average tangential velocity $\overline{V}_t$:

$$\frac{£}{\overline{V}_t} = N_{mp}.(t_{eff} + t_{non\_eff}) = \overline{T}_c - T_0 \tag{17}$$

The expression of the total refining impulse can therefore be obtained in terms of times, instead of lengths:

$$I_T = n_c.\left(1 + \frac{b}{a}\right).\left\{\frac{\overline{T}_c - T_0}{A_T}\right\}.F_n^{net} \tag{18}$$

Expressions of the refining impulse for different technologies of refiners

- For Valley beaters, the average pressure $\overline{P}_1$ is directly calculated from the applied net normal force F_n^{net}. The total overlapping area A_T is given by the product: £. l_0 where l_0 is the length of the roll (rotor). Hence, we obtain:

$$\left\{\frac{\mathcal{L}}{\overline{V}_t A_t}\right\} = \frac{1}{\pi D_r N l_0} \tag{19}$$

where D_r is the diameter of the roll and N the rotation speed (rps).

The total refining impulse is given, as the expression in wet pressing, by the ratio of the linear load of the net normal force to the tangential velocity of the roll:

$$I_T = n_c.\left(1 + \frac{b}{a}\right).\frac{F_n^{net}/l_0}{\pi D_r N} \tag{20}$$

- For disc or conical refiners, the average pressure $\overline{P}_1$ is calculated considering the net tangential force F_t^{net} and the global friction coefficient, f. The net tangential force F_t^{net} is directly calculated from the net power P_{net} and the space average tangential velocity $\overline{V}_t$, as follows:

$$\overline{P}_1 = \frac{F_n^{net}}{\xi A_T} = \frac{F_t^{net}}{\xi A_T . f} = \frac{P_{net}}{\xi A_T . f . \overline{V}_t} \tag{21}$$

Another unified expression of the total refining impulse can be therefore found as:

$$I_T = n_c . \left(1 + \frac{b}{a}\right) . \frac{1}{A_T N} . \frac{P_{net}}{\bar{V}_t . f} \tag{22}$$

If we assume that a disc refiner is the limiting case of a conical refiner where the angle of the cone α_c equals 90°, the product $A_T.\bar{V}_t$ may be expressed taking into account some previous results already published by the authors [4], as follows:

$$A_T.\bar{V}_t = \frac{\pi(\rho_e^2 - \rho_i^2)}{sin(\alpha_c)} . \frac{4\pi N(\rho_e^3 - \rho_i^3)}{3(\rho_e^2 - \rho_i^2)} = \frac{4\pi^2 N(\rho_e^3 - \rho_i^3)}{3.sin(\alpha_c)} \tag{23}$$

The equation (22) can be written as follows:

$$I_T = n_c . \left(1 + \frac{b}{a}\right) . \frac{3.sin(\alpha_c).P_{net}}{4\pi^2 N(\rho_e^3 - \rho_i^3)} . \frac{1}{f.N} \tag{24}$$

Comparing our theory to the published works, it is interesting to understand that the specific edge load, *SEL*, is included in our approach. The *SEL* expression was rigorously given by the authors for single disc or conical refiners [4]:

$$SEL = \frac{3(a+b)^2 .P_{net}}{4\pi^2 N(\rho_e^3 - \rho_i^3)} .sin(\alpha_c) \tag{25}$$

We therefore obtain for the refining impulse the expression, introducing the *SEL*:

$$I_T = n_c . \frac{SEL}{a(a+b)} . \frac{1}{f.N} \tag{26}$$

It appears therefore that the total refining impulse is inversely proportional to the square of the rotation speed (not as the inverse as for the *SEL*). Other parameters such as the global friction coefficient, the number of cycles, or the geometry appear explicitly. Furthermore, the refining impulse for a single cycle, I_1, is controlled by the non-obvious physical quantity:

$$\frac{SEL}{a(a+b)} . \frac{1}{f.N} . \tag{27}$$

Hence, we obtained the expression of the refining impulse for any considered beating technology.

MATERIALS AND METHODS

The experimental refining trials were carried out on a Valley beater, a disc refiner (12″ single disc, Sprout Waldron) and a conical refiner (Escher-Wyss). The pulps were bleached softwood Kraft pulp (BSKP). The mass concentrations for the pulp suspension were fixed in the low consistency regime (2% to 4%) during the refining trials. The pulp properties (SR, WRV) were measured in accordance with ISO standards. The fiber lengths were measured using commercial equipment (Morfi[@]) and the fiber length weighted by length was considered.

Results and discussion

We present results for the different refiners.

- For the case of *Valley beaters*, the net normal force is fixed by the added masses. We present here different results obtained adding a single mass (2; 3.5; 4.5; 5.5; 6.5 kg) during the whole test. The pulp concentration and the roll speed are kept constant during all the trials. Figure 4 represents 95 different experimental conditions.
- In the case of the lightest mass (2 kg), the refining phenomena do not take place inside the gap clearance in "efficient" refining conditions. Indeed, the applied normal force is not sufficient to efficiently refine this pulp. That is why the experimental points are not located on the same single curve obtained for the other masses.

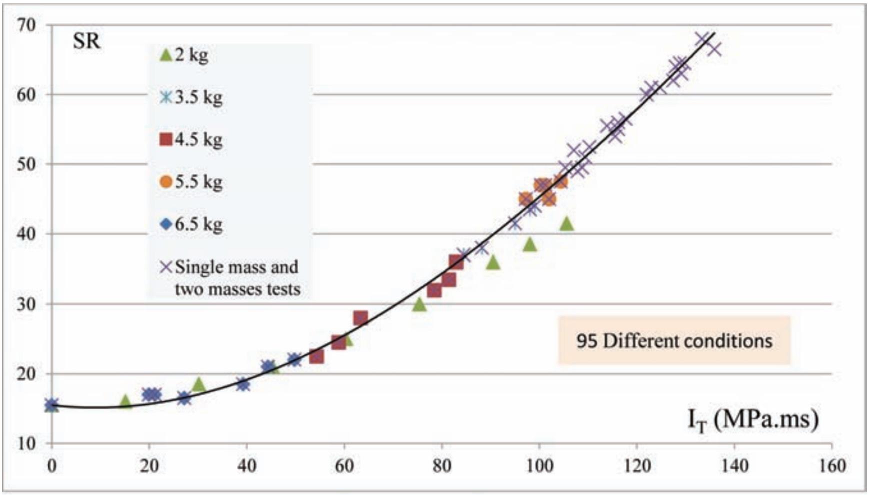

Figure 4. SR vs Applied Impulse I_T (MPa.ms) – Valley beater – Bleached softwood Kraft pulp.

The refining impulse I_T is proved to be a controlling variable for the SR degree of pulp whatever the efficient refining conditions are, as a unique curve SR versus I_T is obtained (Figure 4).

- In the case of *disc or conical refiners*, considering a *given pulp* and a *given refiner*, all trials differ by changing either the refining conditions (net power, rotation speed) and/or the engineering parameters (bar width, average bar crossing angle). The volumetric flow and the solid consistency are kept constant for all the experimental trials.

  We consider first a *reference refining trial,* choosing the numerical value of the global friction coefficient, f_0. Then, we draw the SR curve vs. the calculated refining impulse I_T. The reference curve always presents *a S-shape* whatever the pulp.

  Then, we undertake *p* other refining trials. The numerical values of the global friction coefficient f_k for $k \in [1, p]$ *are unknown*, but estimated as equal to f_0. The curves (SR, I_T) differ from the previous reference curve. Next, we fit the values of the friction coefficient f_k in order to superpose that all the experimental points on the same S-shape curve for the $(p + 1)$ refining trials.

- For *disc refiners*, we modified the net power (P_{net} from 7 to 24 kW), the bar width (*a* from 3.2 to 4.8 mm), the average bar crossing angle (γ from 22.5° to 47.5°). The pulp concentration of the bleached softwood Kraft pulp and the rotation speed were kept constant during the refining trials. The following Figure 5 represents 19 different experimental conditions and corresponds to the same experimental data as on Figure 2(b).

The SR evolution versus the refining impulse I_T is also a unique curve, where the only parameter, *f*, represents the global friction coefficient, fitted for each set of trials.

- For *conical refiners*, the influence of the net power (from 600 to 1800 W) and the rotation speed (from 600 to 1500 rpm) are considered, keeping constant the pulp concentration and the volumetric flow. Figure 6 represents 101 different experimental conditions.

The SR evolution also exhibits a unique curve when the single parameter, *f*, is calculated for each set of trials. It has to be noted that, for all the refining trials, the values found for the friction coefficient, *f*, are in accordance with the

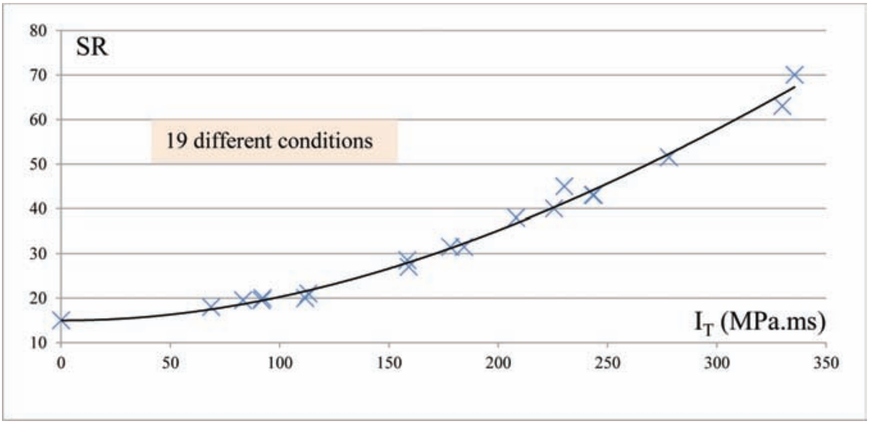

Figure 5. SR vs Applied Impulse I_T (MPa.ms) – Disc refiner – Bleached softwood Kraft pulp

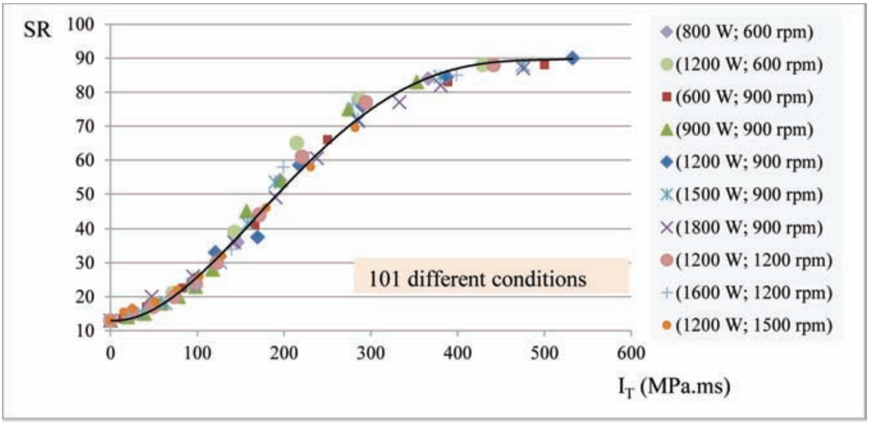

Figure 6. SR vs Applied Impulse I_T (MPa.ms) – Conical refiner – Bleached softwood Kraft pulp.

values found in literature [3] and the ones directly measured on our experimental set-ups.

What happens if we change the nature of the pulp but keeping constant all the refining conditions and all the engineering parameters?

We obviously do not get the same reference curve SR vs I_T. However, we always obtained a universal S-shape curve leading to different numerical values of the friction coefficient, f_k'.

Universal scaling law for the SR degree vs the refining impulse?

As the S-shape of the SR degree vs the refining impulse is always the same qualitatively, we characterize it with numerical values of the SR initial, SR final, SR at the inflexion point. The corresponding refining impulse for the inflexion point also depends on the pulp, on the refiner technology, on the refining parameters, and on the refining conditions. We found 4 numerical parameters (SR initial, SR final, SR inflexion, and I_T_inflexion) to set quantitatively the S-shape curve SR vs I_T, if needed.

To complete the evolution of the properties of the pulp suspension, we measured also the Water Retention Value (WRV) and the fiber length weighted by length. By way of illustration, the results are presented in the case of the conical refiner in Figure 7, for different applied pressures, P_m, for a given rotation speed (900 rpm).

The evolutions of both WRV and the average fiber length (L_f) depend on (i) the refining impulse, and (ii) the average applied pressure. Based on the pressing analogy, we consider these properties to be *Compression Controlled*.

One can observe that the X-axis has not the same maximum value: 300 MPa.ms for the WRV and 600 MPa.ms for the weighted fiber length. The difference between these two maximum numerical values relies on the difference between the two major refining effects on the pulp fibers (fibrillation and cutting). There is no reason to reach maximum refining effects for both properties for the same refining impulse. For example, at I_T = 300 MPa.ms, we decreased the fiber length by 25% but we increase the WRV value by 60%. We can conclude that low refining impulses are *more efficient* for the *development of the internal fibrillation*, rather than that of cutting, which requires higher values of the *refining impulse applied*. Consequently, the value of the refining impulse has to be optimized for each property considered.

The paper properties were also measured (Figure 8). We illustrate here the results considering apparent density (Figure 8(a)), breaking length (Figure 8(b)), burst strength (Figure 8(c)), and tear resistance (Figure 8(d)).

The apparent density increases with increasing pressure applied in the refining zone.

The breaking lengths and burst strengths follow exactly the same ranking.

Considering the tear strength, the fiber lengths have classically to be introduced (Fig. 7(b)) to understand the evolution of the experimental results as a decrease of the fiber length leads to a decrease of the tear resistance.

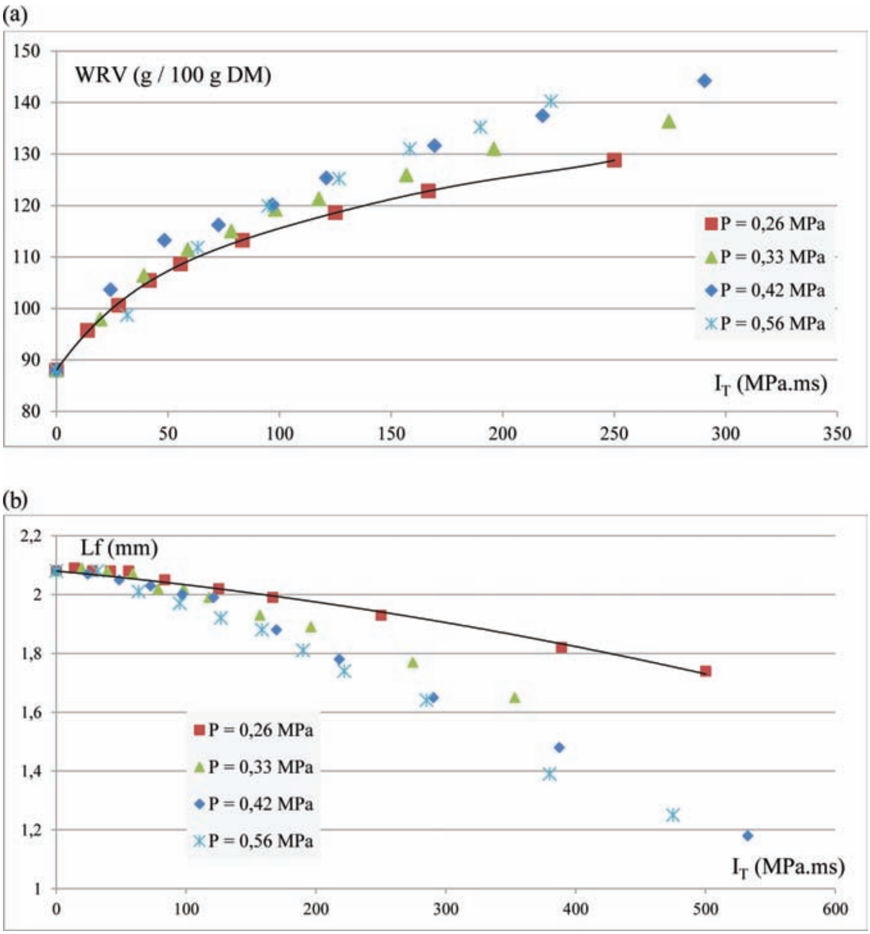

Figure 7. Evolution of pulp properties vs. Refining Impulse I_T (MPa.ms) – Conical refiner – Bleached softwood Kraft pulp: (a) Water Retention Value WRV and (b) Fiber length L_f.

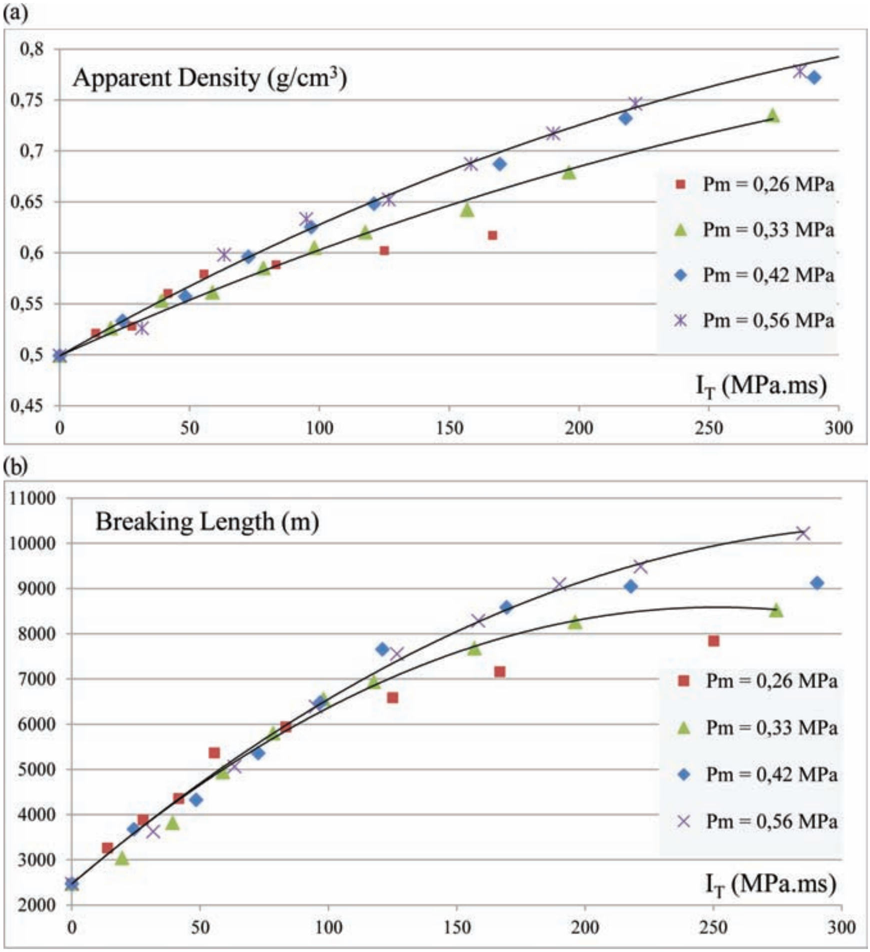

Figure 8. Paper properties for different impulses for a conical refiner: (a) Apparent density, (b) Breaking length

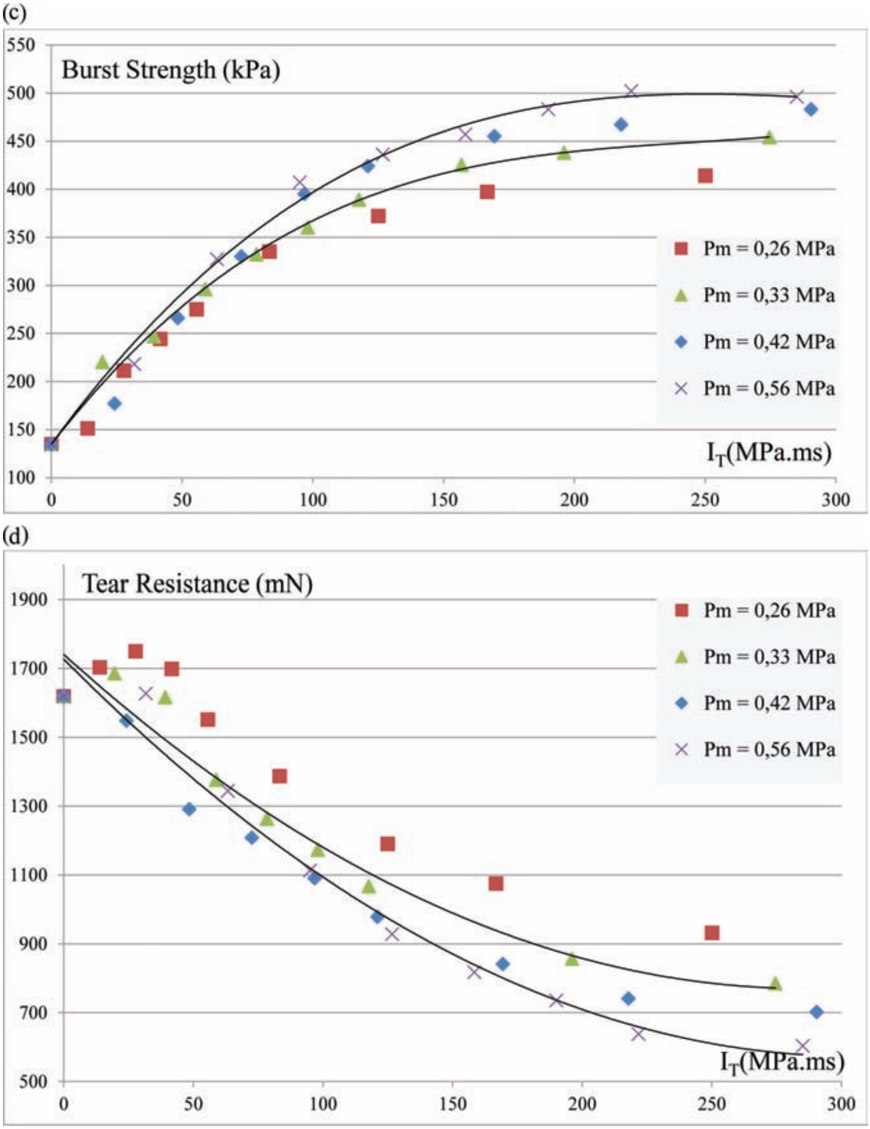

Figure 8 (*cont.*). Paper properties for different impulses for a conical refiner: (c) Burst strength, (d) Tear resistance

CONCLUSION

We successfully analyzed the evolution of the pulp properties (SR, WRV and fiber length) and the paper properties (apparent density, breaking length, burst and tear resistances) based on the proposed refining impulse. All the evolutions demonstrate a single behavior versus this impulsion, whatever the refining technology used. The mean applied pressure in the compression controlled cases has to be introduced as a complementary parameter, similarly to the pressing analysis.

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ANNEX

We illustrate here our approach in the case of a single disc refiner.

We mainly focused on the *average number of crossing points* when the rotor disc is rotating in front of the stator disc, having in mind that all crossing points do not have the same area.

We know that, for each position during the rotation of the rotor disc in front of the stator disc, the number of crossing points varies with time. We carried out these complete calculations. However they are really complex and not really useful. Instead, we preferred to calculate the average number of crossing points.

The calculation of this result was presented in (FRS, Oxford 2001). For a single disc refiner, the triplet (α, β, θ) is given respectively by the grinding angles of (i) the rotor bar, (ii) the stator bar, and (iii) the common sector angle:

$$\overline{N_{cp}} = \int_{\rho_i}^{\rho_e} \frac{2\pi\rho d\rho}{(a_r+b_r)(a_s+b_s)} \cdot \frac{1}{\theta^2} \int_{\alpha}^{\alpha+\theta} \int_{\beta}^{\beta+\theta} sin(\varphi_r+\varphi_s).d\varphi_r.d\varphi_s$$

(with the notations given in the article).

After calculations and simplifications of the sinus cardinal expression (between brackets), we found:

$$\overline{N_{cp}} = \frac{\pi(\rho_e^2-\rho_i^2)}{(a_r+b_r)(a_s+b_s)} \cdot \left[\frac{sin(\theta/2)}{\theta/2}\right]^2 .sin(\alpha+\beta+\theta) \cong \frac{\pi(\rho_e^2-\rho_i^2)}{(a_r+b_r)(a_s+b_s)/sin(\gamma)}$$

As the result of calculation, we obtained that the average number of crossing points $\overline{N_{cp}}$, was the ratio of the constant area of the corona by a *representative constant crossing point area* (or a time average crossing point area). We obtained that the 'lozenge' figure has a *typical crossing angle* which is precisely equal to the *time average crossing angle*. This lozenge also leads, on time average, to an elementary constant bar contact area equal to:

$$a_{cp} = \frac{a_r.a_s}{sin(\gamma)}$$

The bar contact area is hence calculated as follows:

$$A_{cp} = \overline{N_{cp}}.a_{cp}$$

Focusing on the *concept of average velocity,* we *considered average quantities in order to simplify the complex description of the phenomena.*

The next question to be considered is the characterization of *the average path length £* of the pulp suspension inside the disc refiner (as we chose this example of refiner technology for illustrating purposes).

During the rotation motion of the rotor disc in front of the stator disc, the tangential velocity is a linear function of the local radius, ρ:

$$V_t(\rho) = 2\pi\rho N$$

where N is the constant rotation frequency (rps) or rotation speed.

Considering the corona, we can calculate the *spatial average tangential velocity* as follows:

$$\bar{V}_t = \frac{1}{\pi(\rho_e^2 - \rho_i^2)} \int_{\rho_i}^{\rho_e} 2\pi\rho V_t(\rho) d\rho = \frac{4\pi N(\rho_e^3 - \rho_i^3)}{3(\rho_e^2 - \rho_i^2)}$$

We can therefore define an average radius $\bar{\rho}$ as:

$$\bar{\rho} = \frac{\bar{V}_t}{2\pi N} = \frac{2(\rho_e^3 - \rho_i^3)}{3(\rho_e^2 - \rho_i^2)}$$

Hence, the average path £ is defined by:

$$£ = 2\pi\bar{\rho}$$

Introducing the impact length $l_{impact} = \frac{\frac{1}{2}(a_r + a_s)}{cos(\gamma/2)}$, already defined by LUMIAINEN, the number of mini-presses along the mean path is given by:

$$N_{mp} = \frac{£}{\left\{ \frac{\frac{1}{2}(a_r + b_r + a_s + b_s)}{cos(\gamma/2)} \right\}}$$

Finally, the following average quantities are necessary to describe the behavior of the beater or refiner:

$$\left(\overline{N_{cp}}, \bar{V}_t, \bar{\rho}, £, l_{impact}, t_{eff}, N_{mp}\right)$$

Transcription of Discussion

REFINING IMPULSE CONTROLS THE MORPHOLOGICAL MODIFICATIONS OF FIBRES

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Jose Iribarne WestRock

First, that picture was taken at the SONY-ESF beater in Syracuse, New York which is still in operation. So you can take your bath, but . . .

Jean-Francis Bloch Université de Grenoble Alpes

Join me.

Jose Iribarne

Yes.
Very interesting work. My question is about the coefficient *f* that you determined. Is it a function only of the type of beater or would it change with different pulps?

Jean-Francis Bloch

In fact, we have done such experiments for hardwood also, and your point is excellent. The coefficient does really depend on the beater and of course on the pulp. We fully agree that this coefficient has to be calculated, or estimated for each kind of pulp. However, what we have seen, and what is important is, that if you check the order of magnitude of the coefficient of friction we found fitting the curve, it was more or less 0.20–0.22, which is exactly the order of magnitude found in literature. Secondly, a few years ago, we had a PhD student who measured the normal force for a disk refiner and found exactly the same value. However, we do not call this experiment a validation, as we did not identify exactly all the variables used nowadays. So for the moment, all I would say, is that taking into account what we can find in literature, the orders of magnitude are absolutely correct, but we didn't validate our approach yet. We still need to compare the best fit and on the other hand a measurement, to claim that we have validated the model.

Eric Linvill WestRock

Very nice work. First of all, I think it is great to try to pull it altogether in just a few parameters. My question was what if you optimized against some other parameter, for example if you optimized against the fibre length instead of the SR value. Would you then change your conclusions that SR would be a function of impulse and pressure? As optimising against another parameter might change the friction parameter. Which one is right?

Jean-Francis Bloch

I think your question is very interesting. I appreciate it in the sense that we always have to think what is the quality of the paper, and what is the quality of the pulp? In the past, the quality was evaluated considering the product of burst and tear, and then the maximum of the curve gives the best Schopper-Riegler. If you consider fibre length, we know that it will decrease during beating. The kinetics of the evolution of fibre length depends on the applied energy which may affect the cutting of the fibres. I would suggest to start with shorter fibres in order not to spend energy for the fibre cut. So, if you want to maintain the fibre length during beating, what is classically called the fibrillation case, you can use our approach because, as I have shown to you in this case, depending on the final lengths to be obtained, I will identify a given impulse. Then there is the other parameter introduced: the pressure. If you don't want to cut the fibres then you also need to keep this pressure as low as possible.

Peter de Clerck PaperTec Solutions Pte Ltd

Thank you, a very interesting paper. Looking at the graphs it seems that all results fall on standard lines, so we have a more-or-less constant relationship between refining impulse and, e.g., breaking length, tear and burst. This implies a predictable relationship of plotting tear vs tensile. In practice, the papermaker optimizes refining to give the desired paper properties, e.g., adjusting tear by moving from cutting to brushing. Your work implies that there is a standardized relationship between refined fibre properties and that said properties are predictably interchangeable, based solely on refining impulse. However, fibres may only absorb so much energy per impact without shattering. I do not see account taken of this in the presented work.

Jean-Francis Bloch

At least I may try to. First, we wanted to study the pulp properties, and afterwards, if we have the evolution of the water retention value, the length and SR, we have the experience and knowledge, how breaking lengths should evolve. If you modify fibre lengths, you will modify various properties. For example, tear does depend on density, fibre resistance, fibre length, and also stiffness and formation. I didn't say anything about formation. So I do not pretend to say that the results are independent of formation. I completely agree with you. For example here, I did not introduce the optical properties. But it is very well known for decades, that if you want to have good mechanical properties, you will have to decrease optical properties. The role of the papermaker is to make the required compromises.

Peter de Clerck

One of the missing elements seems to be the impact, or the amount of energy going in at each stage in the process. As I say, fibres are limited, some fibres will shatter very quickly when you hit them with refining and sometimes you have to put them through multiple passes. You get the same total amount of energy, but if you put all that energy in one hit, you get a completely different result or set of properties.

Jean-Francis Bloch

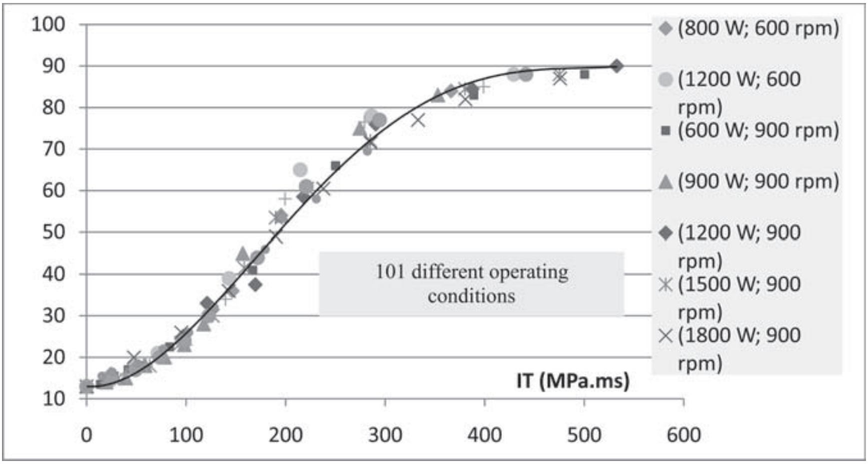
I fully agree and I will try to answer your question considering the analogy with pressing. I can consider one given impulse which is the main factor to be considered. But for this given impulse you can have a longer residence time in a single press, or you can have a multi press. So it is exactly similar. We may consider the total applied impulse, I_T, as $I_T = n.\ I_1$, where n and I_1 represent the number of presses and the impulse for a unique press, respectively.

Do I have to introduce the energy in one single pass, or do I have to consider different lower impulses? This is here exactly the same situation for beating, considering the applied energy. I fully agree with your point. Having in mind, once again, that refining impulse corresponds to the mechanical impulse in pressing.

Harshad Pande Domtar Inc.

Can you go to the slide of Schopper-Riegler versus Impulse, please? Between 400 and 600, it's kind of flat curve. Is it because of the Schopper-Riegler's upper limit is 90 or it flattens out?

Jean-Francis Bloch



It is because I do not believe in the relevance of the Schopper-Riegler for such high values. It does not characterize the evolution of the morphology of the fibres anymore.

Harshad Pande

Right, exactly.

Jean-Francis Bloch

We know that Schopper-Riegler has a limited interest in highly beaten pulp. In the paper industry involved in high beaten pulp, such as cigarette, they developed alternatives such as TAPPI index, or TAPPI factor.

Harshad Pande

So coming to the earlier question. Wouldn't there be another, parameter, fibre length on the Y axis or some other parameter that you would consider.

Jean-Francis Bloch

I am not sure to get your question. Your question is, can I use another index which may be better than the Schopper-Riegler?

Harshad Pande

Yes.

Jean-Francis Bloch

But we started with SR because it is used classically. I do not like really the Schopper-Riegler test, frankly speaking, because it is a non-linear function of beating time. You don't have any significant modification when you consider a highly beaten pulp. So the TAPPI factor, for example, is much better. And I fully agree with you; however, we wanted to consider SR as it is used in industry. But I fully agree, Schopper-Riegler is not good for highly beaten pulp, no doubt.