

Optimisation of the Energy Consumption in the Pulp Refining Operation

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In paper industry, the pulp refining operation enables manufacturing a wide range of fibrous suspensions (pulp) which induce different paper grades. We propose in this paper a methodology for optimizing a refining installation. A standard drainage test ($^{\circ}\text{SR}$) characterizes in paper industry the refined pulp. For the papermakers, the control of the $^{\circ}\text{SR}$ is consequently of primary importance since it is correlated with the end-use paper properties. In this research, refining trials are carried out on bleached softwood Kraft pulp using a laboratory disk refiner running in a batch mode and low consistency (2% to 6% of mass solid fraction). The refining kinetics is analyzed by considering the evolution of the $^{\circ}\text{SR}$ function of the net mass energy consumed. All the curves exhibit an S-shape. At the same net mass energy consumed, the kinetics curves may differ considering the applied net power. Instead of the net power, a more general concept of the refining intensity is used here the net tangential force per crossing point. 4 values of this intensity enable differentiating the experimental trials. It has to be noted that 6 points of net mass energy consumed are considered per intensity. For the covered range of intensity, between 1.4 and 4.3 N, the quickest refining kinetics is obtained for (44.5 +/- 1) $^{\circ}\text{SR}$ which minimizes the required energy consumed at 3.1 kWh/(t. $^{\circ}\text{SR}$) for a softwood pulp. This numerical value is 5 to 6 times less than the industrial ratio 15-20 kWh/(t. $^{\circ}\text{SR}$) classically encountered in industry for printing and writing paper grades.

1. Introduction

In paper industry, the pulp refining operation enables manufacturing a wide spectrum of fibrous suspensions, Page (1989), Peel (1999). These pulps will lead to manufactured papers which will differ by their physical, optical and filtration properties. The drainage resistance of the pulp ($^{\circ}\text{SR}$) is correlated with the end-use paper properties. Therefore, it is of main importance to analyze the evolution of the drainage resistance index of the pulp, from its initial SR_0 to its final value SR_f . This evolution is influenced by the refining energy E_m and the refining intensity I . The refining energy reveals how much energy is consumed per mass of fibers. The refining intensity reveals how this energy is transferred to the mass of fibers and what are the resulting effects on fibers (shortening, hydration, and fibrillation). The net tangential force per crossing point is chosen to describe the refining intensity on fibers among different other indices (Roux et al., 2009).

On a refining installation running in a batch mode and n cycles, if the mass of pulp M (in dry solids) and the mean residence time τ are known quantities then the refining cumulative energy, consumed during time t , is given by the equation:

$$E_m(t) = P_{\text{net}} \cdot t / M = P_{\text{net}} \cdot n \cdot \tau / M \quad (1)$$

So, for a given net power P_{net} applied in a refiner, a decrease of the mass energy E_m induces a decrease of the time t (or a decrease of the number n of cycles). However, we must take into account the necessary increase of the °SR value to reach the required end-use paper properties. That is why we focused our interest on the determination of the ratio $E_m / (\text{°SR}_f - \text{°SR}_i)$, associated with the choice of the refining intensity. In paper industry, for a given paper grade manufactured, the only known quantity is the mass flux of dry solids. The knowledge of both this ratio and of the flux of mass implies the choice of the adequate net power applied in a refiner. In the second paragraph, the materials and methods are presented. Then the third paragraph is devoted to the experimental results and their analysis. A last paragraph dealing with conclusions and perspectives ends up this paper.

2. Materials and methods

2-1 The refining installation

In order to follow the evolution of the °SR in the refining operation, a bleached softwood Kraft pulp was chosen for our laboratory disk refiner installation. The initial pulp had the following characteristics: average weighted fiber length $L_{f0} = 1.85$ mm, water retention value (water content inside the fibers) $WRV_0 = 91$ g of water/100g of dry pulp, drainage resistance index 13.4 °SR, mass fraction of fine elements 2.9%. The pulp mass solid fraction was constant at 3.5% (low consistency range) during the trials. The refining pilot enables analyzing the effects of the net refining energy and of the refining intensity independently. Hence, when a net power is chosen, the refining kinetics is studied by increasing the net cumulative energy. This can be obtained by increasing the time t (or the number n of cycles) according to equation (1). 5 cycles or 6 points of net cumulative energy are studied per refining intensity (including the initial one) and 4 intensities are investigated.

2-2 Methodology chosen for the experimental trials

A disk refiner is a rotor/stator device where the parallel plates in front of each other are fitted with metal bars (colored in plain black), according to the Figure 1.

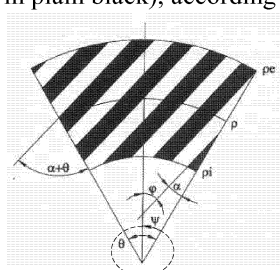


Figure 1: Example of a periodical angular sector θ on a plate of a disk refiner.

The Figure 1 displays one angular periodical sector θ , comprised between the internal ρ_i and the external radius ρ_e of the disk plates. During their relative motion of the rotor in front of the stator, crossing points are generated. We will only consider their mean value as they vary with time. For an experimental trial at a constant rotation speed N , a net power is applied on the refiner. The refining intensity chosen in these investigations is the net tangential force per crossing point. Considering the same bars and groove widths a for both the rotor and the stator, the expression of the refining intensity I is given by the equation (2):

$$I = \frac{3a^2 \cdot P_{\text{net}}}{\pi^2 \cdot N \cdot (\rho_e^3 - \rho_i^3) \sin \theta} \quad (2)$$

As the rotation speed $N = 25 \text{ s}^{-1}$ and the sector angle $\theta = 22.5^\circ$ are kept constant during the trials, we will modify the applied net power and the common bar width (or groove width) in our investigations according to Table 1. The net power is equal for the first and the last trial whereas the bar width is the same for the three first trials.

Table 1: Engineering parameters chosen for the 4 experimental trials.

Trial number	P_{net} (kW)	a (mm)	I (N)	Final E_m (kWh/t)
1	11	4.8	3.14	267
2	14.9	4.8	4.26	276
3	7.2	4.8	2.06	300
4	11	3.2	1.38	375

3. Results and analysis

The Figure 2 displays the $^\circ\text{SR}$ evolution vs. the net mass energy E_m parameterized by the refining intensity I .

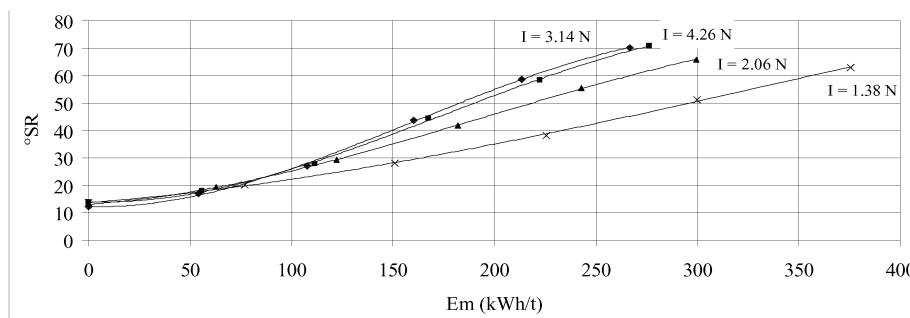


Figure 2: Refining kinetics for the 4 experimental trials performed, each with a constant refining intensity I .

All the curves exhibit an S-shape with inflexion points. The curves corresponding to trials n°1 and n°2 are nearly superposed and the kinetics of trials n°3 and n°4 are slower than those of trials n°1 and n°2.

3.1 Refining kinetics interpretation

On Figure 2, the refining intensity $I = 1.38$ N (trial n°4) induces a slow kinetics of the °SR. Furthermore, the net tangential force per crossing point is not sufficient compared to trial n°1 where $I = 3.14$ N. Between trials n°1 and n°4, only the bar width, a , was modified. According to equation (2), the bar width a , appearing with an exponent 2, has a higher influence on the refining intensity than the net power. For the trial n°4, the bar width $a = 3.2$ mm is too small and leads to a force 2.3 times less compared to the trial n°1. The force in trial n°4 is too small for softwood fibers. In the papermaking practice, it is well known that the bar width of 4.8 mm is adapted to the initial length of softwood fibers. Hence, the value of 3.2 mm for the bar width is too small for softwood fibers.

On the contrary, the three first trials with a refining intensity I comprised between 2.06 and 4.26 N, enable the pulp to be refined with an acceptable kinetics. In these cases, the developed forces in the gap clearance of the refiner are adapted to softwood fibers. It is interesting to observe that the 3 inflexion points are all obtained for the same range of values (44.5 +/- 1) °SR. However, their corresponding net refining energies are increasing from 160, 174 to 194 kWh/t, respectively from the first to the third trial. The refining intensity of the third trial is 34% less than that of the first trial (see Table 1) whereas the cumulative refining energy is increasing by 21 % from the first to the third trial. As the refining kinetics of the third trial is slow, the corresponding net cumulative energy consumed to reach the inflexion point is the highest of the three first trials.

The trial n°1 reveals that the optimal value is close to $E_m = 160$ kWh/t with 43.5 °SR with an optimal refining intensity comprised between $I = 3.14$ and 4.26 N.

3.2 More general analysis

In the preceding paragraph, we were interested by the most efficient refining kinetics in the vicinity of the inflexion point. However, for a given refining intensity I , at any point of the S-shape curve, °SR vs. E_m , the slope can be determined. For example, an empirical model leads to a third order polynomial function for all the four S-shape curves. This enables calculating the slope according to equation (3) where G is a parabolic function, in this case:

$$\frac{d^{\circ}\text{SR}}{dE_m} = G(E_m; I) \quad (3)$$

A given net refining energy E_m is always linked with a unique °SR value of the pulp in an S-shape increasing curve, for a given refining intensity I . Consequently, another expression of equation (3) can be given by replacing E_m by °SR:

$$\frac{d^{\circ}\text{SR}}{dE_m} = F(^{\circ}\text{SR}; I) \quad (4)$$

For the whole set of °SR and refining energies investigated in this experimental campaign, the optimum is reached for the minimal net refining energy consumed E_m to increase the °SR value from its initial °SR_i to its final value °SR_f. This optimum is calculated as follows:

$$\frac{E_m}{^{\circ}\text{SR}_f - ^{\circ}\text{SR}_i} = \frac{1}{^{\circ}\text{SR}_f - ^{\circ}\text{SR}_i} \cdot \int_{^{\circ}\text{SR}_i}^{\circ\text{SR}_f} \frac{dE_m}{d^{\circ}\text{SR}} \cdot d^{\circ}\text{SR} \quad (5)$$

Introducing equation (4) in equation (5) leads to:

$$\frac{E_m}{\text{°SR}_f - \text{°SR}_i} = \frac{1}{\text{°SR}_f - \text{°SR}_i} \cdot \int_{\text{°SR}_i}^{\text{°SR}_f} \frac{d\text{°SR}}{F(\text{°SR}, I)} \quad (6)$$

This curve is displayed in Figure 3. Therefore, a graphical interpretation of the optimum can be given by the mathematical average of the function $1/F(\text{°SR}, I)$, between the initial and final values of the °SR of the pulp during the refining operation. We may also consider a simple criterion based on the length of the plateau for the minimum value.

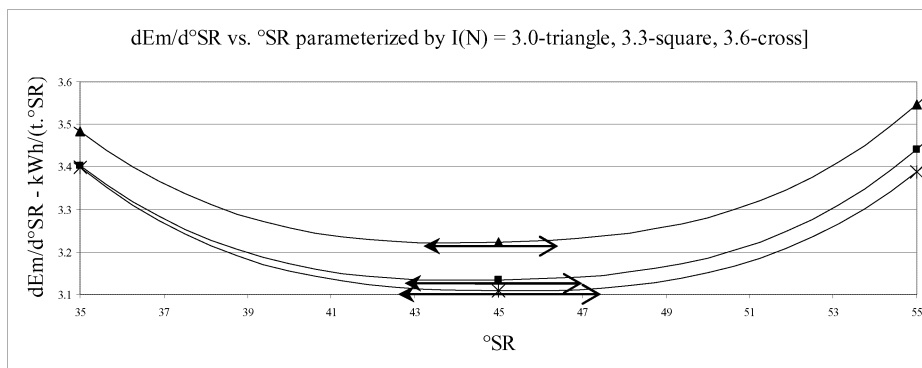


Figure 3: Reciprocal of the function $F(\text{°SR}, I)$ vs. °SR in the vicinity of the inflexion point for 3 refining intensities $I=3.0$ N (triangle); $I=3.3$ N (square); $I=3.6$ N (cross). The arrows represent the domain of stability for the minimum value.

At the end of the preceding paragraph, the optimal refining intensity was supposed to be found between $I = 3.14$ N and $I = 4.26$ N. Therefore, we decided to investigate the range of the refining intensities comprised between 3.0 N to 3.6 N. In this range, all the curves exhibit a U-shape. The minimum of the curves is located at values of °SR which correspond to the inflexion point and are not dependant on the refining intensity. The range of values of °SR for which the ratio $dE_m/d\text{°SR}$ is stable is a function of the refining intensity I . We can observe that the curves show a non linear effect. For the same variation of the refining intensity of 0.3N, the curves for $I = 3.0$ N and $I = 3.3$ N are close from each other whereas the curves for $I = 3.3$ N and $I = 3.6$ N are more separated.

The parabolic-shape is the result of the empirical model (order 3) of the refining kinetics and of its derivation. However, the tendency is independent of the chosen model. For a given intensity, we are interested by the minimum value of the ratio $dE_m/d\text{°SR}$ and by its stability around the inflexion point. The value of the optimal refining intensity obtained here is therefore $I = 3.6$ N. At the inflexion point, for this optimal intensity, the minimum value of the ratio $dE_m/d\text{°SR}$ reaches 3.1 kWh/(t.°SR).

From equation (6), for the optimal intensity, on the interval specified (45 ± 10) °SR, the ratio $dE_m/d\text{°SR}$ has a value of 3.2 kWh/(t.°SR). Now, if one extends the interval of °SR values by (45 ± 20) °SR, the global energy needed increases. In this case, the optimal

solution is found to be 3.5 kWh/(t.°SR). This solution is roughly 5 to 6 times less than the ratio found in the paper literature for printing and paper grades, for example, which is found to be between 15 and 20 kWh/(t.°SR).

4. Conclusions and perspectives

In the low consistency refining of fiber suspensions, the knowledge of the °SR kinetics is of primary importance for the papermaker as it allows the industrial control of the refining operation. Indeed, the final drainage index °SR_f is associated to the end-use paper properties. The required energy consumption per mass of fibers can be determined. Moreover, if this refining energy is overestimated, it can lead to a waste of energy in a refining installation.

In order to determine the value of the optimal refining energy, experimental investigations must be performed on the studied refiner installation running in batch mode. For a given refining intensity, the °SR kinetics is analyzed for different refining energies. By plotting the ratio $dE_m/d^{\circ}SR$ vs °SR, parameterized by the refining intensity *I*, the optimal refining intensity was determined at 3.6 N leading to the minimum of the ratio $dE_m/d^{\circ}SR$ at 3.1 kWh/(t.°SR). Then, considering a variation of (45 +/- 20) °SR, the average ratio was found at 3.5 kWh/(t.°SR) for the softwood pulp. This value is 5 to 6 times less than the ratio in the paper literature which is found to be between 15 and 20 kWh/(t.°SR) for the printing and writing paper grades for example.

The experimentation presented here can be extended to any kind of fibers in order to determine the best adapted refining intensity (or net power) for the most efficient refining kinetics associated with the smallest net refining energy.

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