Understanding the disk refiner

The mechanical treatment of the fibers

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The basic function of paper mill refining is to mechanically condition or "beat" the pulp so that new surfaces are created and fiber-fiber bonding is improved. This improved bonding does not come cheaply; a considerable amount of energy is consumed in a typical disk refiner. Thus, the energy transfer aspect of refining is closely related to strength development of the pulp. Both of these topics will be discussed and a practical theory of relating the refining energy to the strength properties for disk refiners will be presented.

MACROSCOPIC ENERGY BALANCE

An energy balance between the outlet of the refiner (designated by subscript "o") and the inlet (designated by subscript "i") gives (1):

\[ U_2 - U_1 = \frac{1}{\rho} (p_2 - p_1) + \frac{1}{2} (\omega_2^2 - \omega_1^2) + \phi_2 - \phi_1 + Q + W \]  

where

- \( U \) = internal energy of fluid per unit mass
- \( p \) = pressure
- \( v \) = average velocity
- \( \phi \) = potential energy per unit mass
- \( Q \) = heat losses across boundaries per unit mass
- \( W \) = work transferred through shaft per unit mass
- \( \rho \) = density

Neglecting potential energy and expressing the change in velocity in terms of the peripheral speed \( V_o = \pi D D \) where \( D \) is the diameter of the disk and \( \Omega \) is the angular velocity gives:

\[ W = Q + U_2 - U_1 + (p_2 - p_1)/\rho + \pi^2 D^2 \Omega^2/2 \]  

\[ 100\% = 98.5\% + 0.38\% + 1.1\% \]

The numbers appearing after Eq. 2 represent the relative conversion of the shaft work into heat, pressure difference, and velocity increase. These percentages were obtained for a 1.7-m (42-in.) diameter disk refiner operating at 500 rpm with \( W = 20 \text{ kW} \) and metric ton (1.0 hp day/ton). The percentage for the pressure drop and velocity squared terms represent maximum values. Also, the net energy supplied by the shaft is usually greater than 20 kW-hr/ton (1.0 hp day/ton). The percentage heat loss was calculated by taking the difference between the and the sum of the last two terms in Eq. 2 and represents both the heat losses through the shell and the heat transferred by the fluid (specific heat of fluid x temperature difference). The fact that most of the energy supplied by the shaft is converted into heat supports the practice of using the temperature increase of the fluid to calculate the net refining energy (2).

The net refining energy, \( E_{\text{net}} \), is a measure of the specific energy applied to a fiber and the fluid surrounding the fiber. It is calculated by subtracting the idling loss (power required to spin the refiner under no load, with the plates apart, and with fluid between the plates) from the total power applied to the motor and dividing by the pulp flow (oven-dry weight per unit time). If \( E_{\text{at}} \) is the specific total energy, in hp days/ton, then

\[ E_{\text{net}} = E_{\text{at}} + \text{idling loss} / (T/D) \]  

where \( T/D = \text{O.D. tons per day pulp flow} \).

Referring to Eq. 2, the net refining energy is given by:

\[ E_{\text{net}} = Q + U_2 - U_1 \]  

However, since the contribution of pressure and velocity increase to the shaft work is small (approximately 1.5%), the net refining energy and the shaft work are nearly equal. We would prefer to use the change in internal energy, \( U_2 - U_1 \), as a measure of refining, but unfortunately it is difficult (and impractical) to measure Q. It is hoped that Q is constant for a given refiner and is much less than the change in the internal energy of the pulp as indicated in reference (2).

Since \( E_{\text{net}} \) is a direct indication of energy transferred to the pulp, it is convenient to use it as a measure of the amount of refining that has been done. It is also convenient to visualize what happens to an individual fiber in passing through the refiner. The fiber, and the fluid surrounding it, have a certain amount of internal energy transferred to it. Also, the fiber periodically comes in contact with the bars on the plate and is impacted or hit an average number of times in its journey through...
the refiner (3, 4). If we interpret $E$ to be the average energy per impact transmitted from the shaft to a fiber and the suspending fluid immediately surrounding the fiber and $N$ to be the average number of impacts per fiber experienced in passing through the refiner, then:

$$E_{net} = EN/M$$  

(5)

where $M$ is the average weight of a fiber. Note that if $E$ has units of hp day/impact, if $N$ has units of impacts/fiber and if $M$ has units of tons/fiber, then $E_{net}$ will be expressed in hp day/ton. Equation 5, which is actually an identity which quantitatively defines $E$, will be used to relate pulp strength properties to the refining energy.

ENERGY TRANSFER MECHANISM

Continuum Approach

If we assume that it is sufficient to treat the pulp suspension as a continuum, then it must behave like a solid, liquid, or a combination of both. A solid can heat up and dissipate energy by disk friction while a liquid will experience viscous dissipation in the presence of a shear field. A disk rotating relative to a solid surface can transfer energy through sliding friction. The amount of energy transferred depends on the coefficient of friction, $f$, and the average plate pressure exerted normal to the plate $P_p$. If the fiber suspension in the gap between the two disks behaves like a solid material, then the energy per unit mass transferred to the stock, $E_{net,d}$, is given by:

$$E_{net,d} = (1-h)2\pi f P_p (r_1 - r_2)/w$$  

(6)

where

- $\Omega$ = angular velocity
- $f$ = coefficient of friction for a fiber-disk combination
- $h$ = fraction of area filled with grooves
- $w$ = mass flow rate
- $P_p$ = plate pressure averaged over the effective surface area
- $r_1$ = inner radius of the refining zone
- $r_2$ = outer radius of the refining zone

$$g(r_1 - r_2) = \frac{2(r_2^2 - r_1^2)}{(r_2 - r_1)}$$

assuming even wear

$$= \frac{(r_2^3 - r_1^3)}{3}$$

assuming uniform plate pressure

Treating the fiber suspension as a homogeneous fluid we can compute the energy dissipated due to the presence of a shear field.

$$E_{net,e} = 2mn(1-k)2\pi n^{n+1} \left(\frac{r_2^n}{r_1^n} - \frac{r_2^{n+1}}{r_1^{n+1}}\right)$$  

(7)

where

- $m, n$ = fluid properties [see Ref. (6)]
- $\delta$ = gap between the plates

Note that both Equations 6 and 7 predict that a bearing surface, proportional to $(1-k)^{r_1^n-r_1^{n+1}}$, is essential for energy transfer. The plate pressure appears in Eq. 6 as the driving force while in Eq. 7 the gap between the plates determines how much energy is transferred. Of course the gap and the plate pressure are not independent since the gap decreases with increasing plate pressure. The detailed derivation of Eqs. 6 and 7 is given in Ref. (6).

On a macroscopic scale it is likely that disk friction (both fiber to metal and some metal to metal) and viscous dissipation both contribute to the net energy input. This is demonstrated by the fact that pure water will heat up if a moderate load is applied (indicating viscous dissipation and turbulence are present) but at the same time, water alone cannot keep the plates apart under high loads (suggesting that disk friction takes place when fibers are present).

Individual Fiber Approach

Attempts at analyzing what happens to individual fibers in the refining process have not been able to satisfactorily account for the large energy consumption. Van Den Akker (6) has calculated the energy required to peel basic cellulosic filaments from a fiber. He found this energy to be roughly 0.1% of the energy actually consumed. It has generally been accepted that refining is inefficient and that a considerable amount of energy is dissipated in the water surrounding the fibers and does not contribute to useful work (7, 8).

On an individual fiber basis, the details of the refining process are highly speculative. It is reasonable, however, to assume that the fiber is under strain while being impacted by the crossing bars of the refiner tackle. This strain is due to forces acting on the fibers. These forces may be tensile, shear, compressive, or torsional in nature. We will take tensile force as an example although other modes of deformation can be used without grossly affecting the final result. We further assume that the fiber is strained to its elastic limit, thus creating irreversible deformation which is responsible for creating the new bonding sites. As these tensile forces are relaxed, the elastic strain is recovered and the associated energy is dissipated as heat in the surrounding fluid. It is significant to note, however, that the energy used to strain the fiber to its elastic limit is essential to the refining process and cannot be considered as wasted energy. If the modulus of elasticity of a fiber is given by $Y$ and the fiber is strained to some value $\epsilon$, then the energy imparted to the fiber and ultimately dissipated is simply $Y^2/2$. The specific energy per impact, as defined by Eq. 6, is then given by:

$$E_B = Y^2/2$$

(8)

where $p$ is the density of a fiber. Taking the value of $Y = 2.0 \times 10^7$ dynes/cm$^2$, $\epsilon$ to be 0.03, and $p$ to be 1.6 g/cm$^3$, (9), the specific energy per impact is 2.4 kwh/metric ton or 0.12 hp dayton. The net refining energy can be estimated using Eq. 6 if $N$, the number of impacts per fiber, is known. Using the expression derived in the Appendix and described below, typical values of $N$ for one pass through a 1.2-m (44-in.) disk refiner are 50 for hardwood and 340 for softwood. This results in refining energies of 120 kwh/metric ton (6.0 hp dayton) for hardwood and 410 kwh/metric ton (41 hp dayton) for softwood. These values are in the order of magnitude of energies commonly encountered in refining. The above calculation represents a more realistic approach to the refining process and explains why such high refining energies are necessary for proper treatment of the fibers.

REFINING VARIABLES

While it may not be possible to establish a clear cause and effect relationship for the kind of refining energy transfer that is possible to measure this energy and thus have an indication of the amount of refining that has been done. It is also possible to measure the effect of refining on the physical properties of the pulp and the final sheet. At the same time, it is desirable to relate these changes in physical properties to variables that are fundamental to the refining process and that take into account the significant details of the process.

We postulate that $E$, the energy per impact, and $N$, the number of impacts, are fundamental refining variables. We further assume that in the refining process, the fibers are impacted by the bars in a calculable manner. Specifically, we assume that the average number of impacts experienced by a fiber in passing through the refiner is given by:

$$N = n r_1 r_2 \sin \alpha$$

(9)

where

- $n$ = number of bars on the rotor
- $r_1$ = number of bars on the stator
- $\alpha$ = residence time of the fiber in the refiner
- $r_2$ = probability that a fiber will be in a position to be impacted

An equation similar to Equation 9 has been suggested by Brecht (3) to calculate the total edge length per second, $L_e$. 

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where $L$ is an average bar length. Similarly, Danforth (4) proposed an expression for the number of impacts in terms of $L$, the throughput, and the consistency. Equation 9 is preferred, however, since it is dimensionless, relatively simple, and appears to include all the pertinent variables.

The residence time in Equation 5 can be replaced with $ALq$ where $L$ is the average groove length, $q$ is the volumetric flow rate, and $A$ is the area available for flow. Also, assume that the majority of the fibers travel in the grooves and that an impact occurs when a fiber finds itself at the edge of a bar. The probability that a fiber will be in position to be hit can be approximated by the ratio of the projected area of a fiber, $A_f$, to the cross-sectional area of a groove, $A_g$.

In the Appendix the number of bars and grooves and the area terms discussed above are given in terms of plate parameters. This results in the following expression for $N$:

$$N = \frac{\pi^3}{4} \left( \frac{D_m}{W_m} \right) \left( \frac{L_g \cdot D_f}{q} \right)$$

(11)

where $D_m =$ mean diameter of refining zone $= (D_f + D_s) / 2$

$W_m =$ groove width + groove width/2

$L =$ groove length

$f =$ number of revolutions per unit time

The energy per impact can be obtained using Eq. 6, which in reality is the defining equation for $E$, provided $E_{net}$ is measured and $N$ is calculated using Eq. 11. Thus, the fundamental variables $E$ and $N$ can be calculated by knowing the particular plate parameters, the pulp flow rate, the refiner speed, the net refining energy, and the average fiber weight and dimensions.

**CORRELATING PROPERTIES**

Previously published data (4, 10) indicate that strength properties can be improved at a given drainage resistance by gentle refining at low energy loads. This corresponds to low energy per impact levels or refining at a high number of impacts. This behavior is demonstrated in Figs. 1 and 2 in which the properties tensile, breaking length, burst, percent elongation, bulk, tear and fold are plotted against Williams slowness for a particular baled hardwood kraft pulp. The high and low $E$ refining was achieved by disk refining in a 0.03-m (12-in.) diameter refiner [see Ref. (2) for schematic of the refining system]. Also included in Figs. 1 and 2 are the results of the same pulp refined in a Valley beater. From these data, it can be seen that disk refining can produce a pulp with a wide range of strength properties and, at the proper conditions, with a higher strength at a given slowness than even the Valley beaten pulp.

It is possible to quantify results similar to those shown in Figs. 1 and 2 provided $E$ and $N$ are, in fact, fundamental variables. For example, let $T$ be any strength property or slowness, and $\Delta T$ be the change in this property due to refining. If $E$ and $N$ are fundamental refining variables, then, for a given pulp, specification of these two variables completely determines the value of $\Delta T$ or

$$\Delta T = g(E, N)$$

(12)

where $f$ is a function of $E$ and $N$ only. Note that since $E = E_{net} / M$, Eq. 12 implies that, for a given pulp ($M$ known), we can also say:

$$\Delta T = g(E_{net}, N)$$

(13)

where $g$ is a function, different from $f$, of the net refining energy and the number of impacts.

The functions $f$ or $g$ can be determined by a sufficient number of experiences. Once this is done, we have a means for predicting $\Delta T$ even if changes are made in the plate pattern, operating conditions, or energy input.

The postulate given above allows us to relate any two physical properties in a functional form with only one independent parameter. For example, if $\Delta T$ is the change in tensile and $\Delta S$ is the change in slowness due to refining, then

$$\Delta T = f_1(E, N)$$

(14)

$$\Delta S = f_2(E, N)$$

(15)

Equation 16 indicates that there is a unique relationship between tensile and slowness provided $N$ is constant. For different $N$'s there is a family of curves of $\Delta T$ vs. $\Delta S$ with $N$ as the parameter. Also, we can maximize $\Delta T$ at a given $\Delta S$ merely by choosing the proper $N$.

To demonstrate this approach, baled hardwood pulp was refined in a 0.3-m (12-in.) diameter experimental disk refiner with a set of plates having 0.005-m (3/16-in.)-wide bars and grooves and a bar angle of 60°. The plates were rotated in both directions and the refiner was operated under various loads. Several energy per impact levels were obtained ranging from 1.24 to 11.3 ergs. The pulp was re-circulated through the refiner and samples taken at different times to obtain values of $N$ between zero and 200 [see (2) for procedure and
small modifications in plate design and the direction of rotation greatly influence the slowness development. The functional dependence of Williams slowness on $E$ and $N$ was found to be (16):

$$\Delta S = \text{constant} \times (EN)^{0.38}$$  \hspace{1cm} (18)

where the constant is $0.79 \times 10^{-4}$ for negative rotation and $1.13 \times 10^{-4}$ for positive rotation for the data shown in Fig. 5.

The difficulties encountered in correlating the slowness development indicate that the type of impact and the localized treatment the fibers undergo are very influential in altering the drainage resistance of the pulp. No doubt, this is tied in with the harm done by cutting fibers vs. fibrillation and the production of fines that results when a cutting action is present. Tensile, on the other hand, is not influenced in the same way. The fact that the change in tensile is linear in $N$ suggests that each impact creates a certain number of bonding sites and the tensile increases proportional to the number of bonding sites. Also, the localized fiber treatment or type of impact does not greatly influence the number of bonding sites made available.

The above results are consistent with the findings of Ingmanon and Andrews (11). They found that a small amount of fines has a great effect on the filtration resistance (different constant in Eq. 16 for positive and negative rotation) but had only a small effect on the tensile strength (one constant for both positive and negative rotation in Eq. 17).

**MINIMIZATION OF ENERGY**

There are practical limitations to operating at low values of $E$. Low energy per impact usually means low refining energy which in turn means that the idling losses will be a larger fraction of the total energy input. If we try to decrease the fraction by applying higher loads, the strength properties of the pulp will suffer due to refining at high energy per impact levels. The basic theory that has been presented can be used to analyze this optimization problem.

The total specific energy for a single refiner is given by Eq. 3. Further, if we consider a given application, i.e., fixed set of plates, consistency, speed of rotation, and a given pulp, then we can express $N$ as given by Eq. 11, in terms of the throughput, in tons per day. Typically for a 1.1-m (44-in.) diameter refiner and hardwood pulp:

$$7ID = 9000N$$  \hspace{1cm} (19)

Now consider the case when we want to refine to a given tensile strength. Using the correlation in Eq. 17 and Eqs. 3, 5, and 19 we can express the total refining energy in terms of $\Delta T$ and either $N$ or $7ID$ as in Eqs. 20 and 21:

$$E_{1s} = \frac{\text{idling loss}}{9000N} + \frac{\Delta T^{0.66}}{0.11 \times 10^4 N^{1.66}}$$  \hspace{1cm} (20)

Fig. 3. Tensile vs. slowness for baled kraft hardwood at 3% consistency, 0.3 m (12-in.) disk refiner with positive rotation.

Fig. 4. Tensile vs. slowness for baled kraft hardwood at 3% consistency, 0.3 m (12-in.) disk refiner with negative rotation.

Fig. 5. Williams slowness vs. net refining energy for baled kraft hardwood at 3% consistency, 0.3 m (12-in.) disk refiner with both positive and negative rotation.

Fig. 6. Dependence of tensile on the number of impacts for three different pulps at a constant energy per impact.
Equations 20 and 21 predict that there is an optimum N or T/D that will minimize the total refining energy at a given value of $\Delta T$. This optimum is shown in Fig. 7 for a $\Delta T$ of 1000 and 1500 m and for an idling loss of 27 kW (50 hp). It should be kept in mind that while Eq. 21 is a theoretical prediction for a 1.1-m (44-in.) refiner, it is based on experimental results (Eq. 17) and is exact for the 0.9-m (12-in.) refiner provided Eq. 13 applies, and $\Delta T$ and either $E$ or $N$ are kept within the range of the data for which the correlation is valid.

The above procedure can be applied to optimizing $E_o$, to obtain a given slowness. Using the slowness correlation, Eq. 18, with a constant of $0.8 \times 10^4$ and Eqs. 3, 5, and 19 results in:

$$E_o = \frac{\text{idling loss}}{N} + \frac{\Delta S \cdot 0.61}{3.06 \times 10^{-4} (\Delta S \cdot 0.61)^{1/2}}$$

This result is shown plotted in Fig. 7 for $\Delta S = 20$ sec and 30 sec. For a 1.1-m (44-in.) diameter refiner, a typical production rate would be 100 tons per day. Figure 7 indicates that this value of $\Delta S$ is far from the minimum for a given $\Delta T$ and that 20-40 kW-metric ton (1-2 hp-dayton) total energy can be saved if the refiner is operated at the optimum value. If the refiner is optimized with respect to slowness only, however, the savings in total energy is minimal.

The above example was given to illustrate the usefulness of the theory and to demonstrate why we would want to be concerned with fundamental variables. Only tensile and slowness were considered here; however, any handsheet property or physical property affected by refining could be treated in a similar manner.

**APPENDIX**

**Derivation of the Number of Impacts**

The number of impacts per fiber is assumed to be proportional to the number of bars on the stator, the number of bars on the rotor, the speed of rotation, and the residence or dwell time for a given fiber. The probability that a fiber will come in contact with a bar is proportional to the ratio of the cross-sectional area of a fiber over the cross-sectional area of a groove or $A_f/A_g$. We can express this as:

$$N = n_r n_b \Omega \tau (A_f/A_g)$$

where

- $n_r$ = number of bars on the rotor
- $n_b$ = number of bars on the stator
- $\Omega$ = rotational speed of the rotor
- $\tau$ = average residence time for a fiber
- $A_f$ = average projected cross-sectional area of a fiber
- $A_g$ = cross-sectional area of a groove

We now assume that these are the only factors that determine $N$. Equation A1 can be put into a different form by representing $n_r$ and $n_b$ by:

$$n_r = \frac{\pi D_m}{w_b} \quad n_b = \frac{\pi D_m}{w_g}$$

where

- $D_m$ = mean diameter ($D_1 + D_2$)/2
- $D_1$ = diameter of inner refining zone
- $D_2$ = plate diameter
- $w_b$ = bar width
- $w_g$ = groove width
- $w_m = w_b + w_g$ = (width of bar + groove)/2

The residence time is found by dividing the groove length, $L$, by the average velocity of a fiber passing through the groove,

$$\tau = \frac{L}{V} = \frac{L}{A/q}$$

where

- $L$ = groove length ($D_1 - D_2$) \cos $\alpha$
- $A$ = area available for flow = $2\pi D_m$ $kh$
- $h$ = fraction of area filled with grooves
- $q$ = flow rate

Thus, when the stator and rotor are identical,

$$\tau = \frac{2\pi D_m}{k} \frac{q}{L}$$

The area ratio, $A_f/A_g$, can be found noting that to a first order approximation the projected cross-sectional area of a fiber is simply

$$A_f = D_f L_f$$

where $D_f$ = fiber diameter and $L_f$ = fiber length; also,$\quad A_g = w_g h$ so that

$$\frac{A_f}{A_g} = \frac{L_f}{w_g h}$$

Equation A1 can now be written:

$$N = \frac{\pi^3}{4} \left( \frac{D_m}{w_m} \right)^3 \left( \frac{L_f}{w_g} \right)$$

**LITERATURE CITED**

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