

ENERGY CONSIDERATIONS IN THE BEATING OF PULP

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Abstract

The incentive to intensive research on the development of radically new beating principles lies in the magnitude of the difference between the energy actually expended in beating and what, under the most ideal conditions, would be needed to modify the fibre in the desired way. Accurate information on the efficiency of existing beating processes does not exist. After a review of some of the estimates of beating efficiency, this paper presents discussions of the energies required in idealised mechanisms to produce certain modifications of the fibre. Idealised mechanisms have been invoked for the purpose of obtaining estimates of the order of magnitude of the power reduction that might be effected through the development of new beating principles. An analysis of the energy and force required to peel basic cellulosic filaments from a fibre, as a function of angle, is presented. This analysis shows that the probability of large-angle fibrillation is much greater than that for small-angle peeling. Estimates of the energy requirement are presented for the development of specific surface through fibrillation of the fibre surfaces, loosening of the internal structure of the fibre and for fibre cutting. It is concluded that a tremendous gap exists between the level of energy now expended in beating and refining and what would be consumed in nearly ideal processes.

THERE are numerous industrial operations in which energy is cheerfully expended to obtain quality — even when the efficiency is reckoned to be

essentially zero. Beating and refining may remain good examples of this comment for years to come. But hundreds of technical men and executives earnestly hope not, because the cost of stock treatment is a significant economic item, amounting to 3 – 4 dollars for each ton processed or approximately 2 – 3 per cent. of the cost of the pulp; when an unusual degree of beating is required, the cost may be five times larger.

If, as some people guess, the efficiency of the beating process is at least 25 per cent., there is, indeed, little incentive to invest large sums of money in research efforts directed to the development of radically new beating principles. The driving potential for such efforts may be assessed by the difference between the energy actually expended in beating (typically 400 kWh./ton) and the work needed, under the most ideal conditions, to modify the fibre in the desired way. If the idealised energy requirement turns out to be orders of magnitude less than that currently expended, there should be much room for the development of really new beating systems. In a larger economic sense, the savings might extend appreciably beyond the energy reduction resulting from improved efficiency; for example, it might be possible to treat the fibre in such manner as to lessen the filtration resistance of the stock on the papermachine wire while retaining the desired properties in the end product.

In a mechanical study of the beater and its action (which, if published today, would be as good and almost as timely as it was 34 years ago), Sigurd Smith⁽¹⁾ identified needlessly large energy losses in a Hollander beater. Two of the mechanisms of loss accounting for an appreciable percentage of the power delivered to a beater are whipping (inelastic impact of the flybars and the stock, accelerating the latter to a velocity equal approximately to that of the flybars) and stock/stock friction. Incidentally, a very small fraction of the power going into whipping is utilised in raising the stock over the backfall of the beater; this small increment in the potential energy of the stock is dissipated in friction to movement of the stock around the tub and the movement is a consequence of the depth gradient. It is not true that the beater consumes an unnecessarily large amount of power in circulating the stock around the tub.

We are concerned with the effectiveness and efficiency of the action on the fibres in the gap between the bars — when all mechanisms of energy consumption not directly and effectively contributing to beating are allowed for. Strachan⁽²⁾ believed that cellulose has a large capacity to absorb energy and that in a properly operated beater (Hollander type, metal bars or stone roll) “a large proportion of the energy apparently disappears, being absorbed directly by the cellulose during fibrillation and appears as an increase in the

electrical surface charges on the beaten cellulose." It is problematical that the energy absorbed by the cellulose is mostly associated with the development of specific surface of the pulp in this way. Wet pulp fibres are visco-elastic (with heavy emphasis on the prefix of this word) and, hence, provide a medium in which mechanical energy can be converted to thermal form through frictional effects of various sorts (such as fluid friction, surface friction, internal friction) when the medium is subjected to hydrostatic, compressive and shear stresses. To be sure, some of the energy dissipated within the fibres should be associated with bond breaking and molecular chain slipping, but it seems likely that nearly all of the mechanical energy which seems to be absorbed by the cellulose is in reality converted through dissipative effects to thermal energy. In a recent work on the use of temperature rise of stock on passing through a Jordan for refining control, Kraske and Koon⁽³⁾ made energy balances. Their data "indicate that, with the exception of the energy consumed by bearing friction, all the energy transmitted to the Jordan rotor appears as sensible heat in the stock." The experimental error in this work was such that internal energy changes in the pulp other than the change of "sensible heat" could have been a few per cent. Higgins and Harrington⁽⁴⁾ arrived at an estimate of the efficiency of the beating process through order of magnitude estimates of two energies. They estimated that the increase in rupture energy of the paper produced annually in Australia is about 100,000 kWh., which is 0.001 of their estimate of the energy expended in beating and refining the pulp from which the paper is made, namely, 100 million kWh. They took this to mean that the efficiency of beating and refining is about 0.1 per cent. The writer fails in his attempt to find a clear interpretation of this comparison of energies. It might be argued that the most ideal beating action would break only those bonds in the fibre which would re-form, at the same energy levels, to create bonds in the paper which would contribute to the tensile strength of the paper. If this is the rationale of this means for estimating efficiency, the efficiency would have to cover the whole operation of beating, refining, papermaking and the term becomes vague. If efficiency is defined as the ratio of the energy required in the most ideal process to modify the fibre in a desired manner to that actually expended in a beating engine, surely there would be many bonds that would re-form in the papermaking operation with little or no contribution to the sheet strength; for example, many bonds ruptured *within* the structure of the fibre will re-form during drying and it is presumed that many of the sub-microscopic fibrils projecting from the surface of the fibres will be pulled back on to the parent fibres by surface tension forces and re-form bonds which do not contribute to the paper strength. Moreover, nearly all of the

energy required to break a strip of paper is consumed in processes other than that of breaking bonds between and within the fibres; in the main, these processes are the storing of strain energy in the strip (which is transferred to kinetic energy of jerk which, in turn, becomes converted to thermal form) and the dissipation of energy in mechanisms related to creep. Both of these energies are roughly proportional to the length of specimen, so that what might seem to be the energy required to break bonds depends upon the test span (ordinarily great compared with the local region of failure) and in reality is largely converted to thermal form. In the writer's opinion, the energy required to break the bonds between and within the fibres is a minute fraction of the energy expended in breaking the paper strip. Efficiency based on the Higgins and Harrington method would then have to be corrected downward to a value which would be very small, indeed, compared with 0.1 per cent.

These introductory remarks should serve to indicate that we have virtually no definite information on how far we could go with truly radical innovations in beating to improve the efficiency and perhaps also the effectiveness of stock treatment. Theory cannot provide us with an exact answer, but theoretical considerations can furnish the basis for discussions, which shed a little light on the subject.

The simple calculation of the energy required to break bonds cross-linking cellulose 'strings' is overidealised, because we shall probably never have a beating principle (whether mechanical, hydraulic, sonic, etc.) that could break bonds without deforming the fibre or some portion of the fibre. Such deformation necessarily requires an expenditure of energy over and above that required to break bonds. Accordingly, we may seek a model mechanism for which the concomitant energy of deformation is minimised.

Assumptions concerning the fibre and its modifications caused by beating

The discussions presented in this paper assume that the structure of the pulp fibre and the modification of the structure caused by beating are essentially as described by Cottrall⁽⁵⁾ in a very interesting paper incorporating the ideas of the many people who have developed the modern concepts of cellulose and cellulosic fibres. It is arbitrarily assumed that the basic cellulosic filaments are like the dense and well-ordered sub-microscopic fibrils described by Meyer⁽⁶⁾ and by Rånby;⁽⁷⁾ in the interest of definiteness, these have been assumed to have a cross-sectional area equivalent to a circle of diameter 80 Å and an elliptical section having a major axis equal to twice the minor axis. We are here concerned with order-of-magnitude calculations and, hence, the accuracy of our assumptions is not of much concern except for a later calcula-

tion involving the specific surface of the basic filaments; here, we can only hope that our estimate of the mean perimeter of the basic filaments is not subject to error greater than about 20 per cent. It is assumed that the energy required to break the hydrogen bonds cross-linking the cellulose filaments is 5 kc./mole.⁽⁸⁾ The Meyer and Lotmar⁽⁹⁾ model for the cellulose molecule and crystalline structure and the Meyer and Lotmar calculation for Young's modulus for the basic cellulose filament ($E=12 \times 10^{11}$ dynes/cm.²) are arbitrarily adopted for our purposes. The density of the cellulosic filaments is taken to be 1.6 g./cm.³

Of the various published articles to discuss the interaction between cellulose and water, the effects on pulp fibres of beating and the probable phenomena that occur when a sheet is formed and dried, the writer has been most impressed with three papers by Campbell⁽¹⁰⁾ and two by Cottrall.^(5,11) In the later of his two papers on the relation to the beating process of cellulose and fibre structure, Cottrall states that beating produces four mechanical effects —

- (1) Transverse subdivision by sharp cutting.
- (2) Transverse subdivision by blunt cutting.
- (3) Internal fibrillation, which entails loosening of the fibrillae and making the fibres more pliable without any appreciably noticeable difference in the external appearance of the fibre; it explains what the beaterman terms 'softening' the fibre.
- (4) Extended displacement of the fibrillae, resulting in visible fibrillation, which, carried to its extreme, results in complete subdivision of the fibre into separate fibrillic entities.

"Varying the proportions of these different types of subdivision represents the whole variation in processing fibres which it is possible to effect by beating. Nothing further can be effected by beating. The whole art of beating is to vary at will the proportions of these different types of subdivision."

It is fairly generally believed that, in addition to cutting, the major effects of beating are to tear or peel fibrils from the fibres and to separate to some extent the filaments within the fibre; these are currently measured and expressed as specific surface and specific volume, respectively, of the wet, beaten pulp. There is also a quite general feeling that, for many papers, it would be advantageous to beat in such manner as to increase the type of fission within the fibre that results in loosening of the structure (increase of wet specific volume) relative to the type of bond breaking that produces fibrils. Gally⁽¹²⁾ states that "The net desired effect in mechanical working is probably that of a general multifilament effect with no actual splitting off of branches or portions of the structure as is evident in fibrillation." He also said that "Unpublished experiments in the author's laboratory [Gally's] have shown clearly that a

relatively high order of bursting strength with good maintenance of tear strength can be attained with no visible indications whatever of fibrillation as viewed under high magnification." This, however, should not be interpreted to mean that cellulosic filaments, perhaps in very large numbers, were not partially peeled away from the fibres. Such filaments waving around in the water surrounding the fibre — jerking about would be a more apt description — could not possibly be seen with an optical microscope of the highest magnification and an attempt to view the filaments in an electron microscope would fail because, in preparing a dry specimen, surface tension forces would cause the filaments to be drawn back into contact with the body of the fibre; if wet specimens could be viewed in the electron microscope, Brownian motion would probably fuzz the image to such an extent as to make the image invisible. There is strong indication that the partial peeling away of cellulosic filaments is important to good interfibre bonding. The evidence for this is found in the interesting series of experiments conducted by Edge⁽¹³⁻¹⁵⁾ on the influence on strength development of tension during drying and in Steenberg's explanation for the phenomenon.⁽¹⁶⁾ Accordingly, we shall consider fibrillation (and the associated development of specific surface of the fibre) as an important aspect of the desired mechanical treatment of pulp.

**Some energy considerations in connection with
idealised mechanical actions**

We shall consider first the energy required to pull (by any imagined agency) a basic cellulosic filament from a fibre. We are not concerned just yet with the origin of the force through which energy for this process is transmitted; it may be mechanical friction, entanglement, an ephemeral making and breaking of bonds with neighbouring fibres or fibrils, fluid friction and so on.

The filament is imagined, as depicted in Fig. 1, to be pulled away from neighbouring filaments on the surface of a fibre (represented by the vertical line) at any angle, θ . The mean pulling force, P , is that required, during steady-state pulling away of the filament, to break the bonds that exist between the filament and the fibre. The instantaneous length of filament removed, z' , is longer than the initial length, z , because the filament is stressed. A portion of the energy expended becomes strain energy of the portion of the filament that has been removed and the remainder of the transmitted energy is expended in breaking n bonds per centimetre length of the original attachment of the filament with other filaments. Immediately prior to the steady-state pulling away of the filament, a small and not completely negligible amount of energy was expended in bending the filament; for our present purposes, the

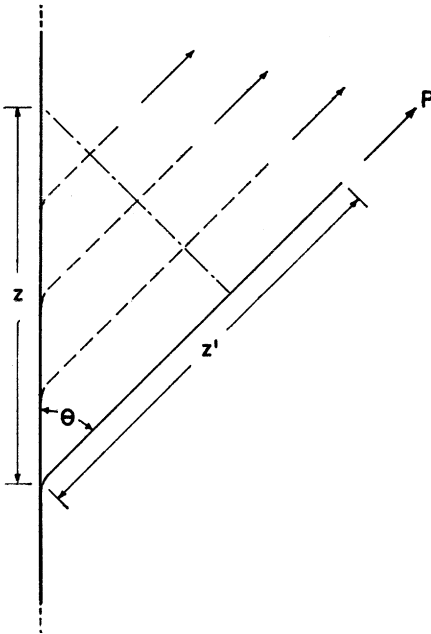


Fig. 1

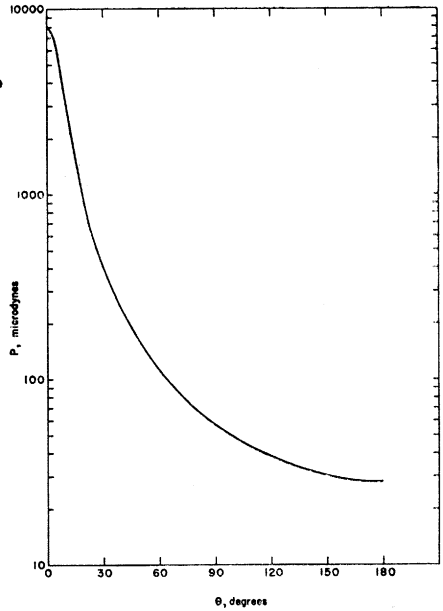


Fig. 3

strain energy associated with the bending of the filament is neglected — there is a good chance, in any case, that this energy is expended in the breaking of the last of the bonds between the filament and the fibre to be broken (this cannot be the case for the strain energy in the whole length of removed

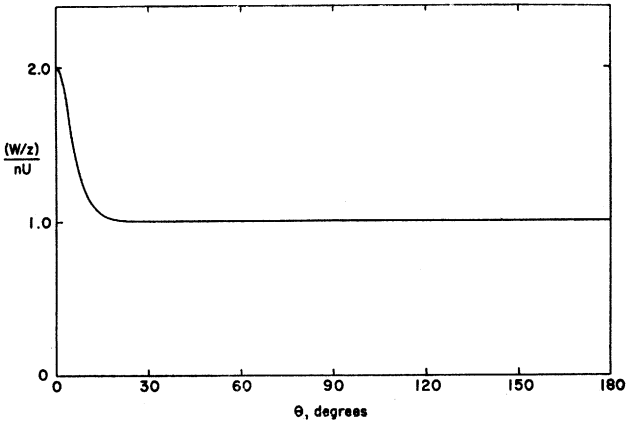


Fig. 2

filament). The energy expended in pulling away an initial length z of a filament is equated, in equation (1), to the sum of the energy required to break nz bonds (U being the energy required to break each bond) and the strain energy stored in length z' of the removed filament (the last term in the equation). In equation (1), E is Young's modulus for a basic cellulosic filament and A is the initial cross-sectional area of the filament.

$$(EA/z)(z' - z)(z' - z \cos \theta) = nzU + (EA/2z)(z' - z)^2 \dots \dots \dots (1)$$

On making the substitution, $f=2(1 - \cos \theta)$ and, solving equation (1) for the work expended per unit initial length of the filament, one obtains equation (2) —

$$W/z = 2nU - (EAf^2/4) [(1 + 8nU/EAf^2)^{1/2} - 1] \dots \dots \dots (2)$$

The ratio of this energy expenditure to that which would be necessary only to break bonds, $(W/z)/nU$, is presented in graphical form in Fig. 2, for the following values of the quantities involved in equation (2) —

$$\begin{aligned} n &= 1.7 \times 10^8 \text{ cm.}^{-1} \\ U &= 3.5 \times 10^{-13} \text{ erg/bond} \\ E &= 12 \times 10^{11} \text{ dynes/cm.}^2 \\ A &= 5.0 \times 10^{-13} \text{ cm.}^2 \end{aligned}$$

The estimate of n , the number of hydrogen bonds per centimetre length of a basic cellulosic filament with which it is attached to neighbouring filaments, was made in the following way. The specific surface of the arbitrarily adopted cellulosic filament is easily shown to be $1.03(a+b)/\rho ab = 3.09/3.2b = 3.4 \times 10^8 \text{ cm.}^2/\text{g.} = 340 \text{ m.}^2/\text{g.}$, when a and b , the major and minor semiaxes, are in the ratio of 2:1 and the cross-sectional area $\pi ab = 2\pi b^2 = 5.0 \times 10^{-13} \text{ cm.}^2$. If each anhydroglucose unit on the surface of the filament could engage in one hydrogen bond,⁽⁶⁾ the number of potential sites per unit length of filament would be the surface area $(1.03\pi(a+b)) = 3.09\pi b$, in this case) divided by the area per anhydroglucose unit $(8.35 \times 5.12 \times 10^{-16} = 4.27 \times 10^{-15} \text{ cm.}^2)$ — or $6.4 \times 10^8 \text{ cm.}^{-1}$. In a dissertation recently completed by Merchant,⁽¹⁷⁾ the specific surface in a fully bleached Mitscherlich spruce sulphite pulp made available for nitrogen absorption by liquid exchange and drying from non-polar solvents like *n*-hexane and *n*-pentane was very high — in the range 80 — 160 $\text{m.}^2/\text{g.}$, the exact value depending upon the surface tension of the solvent at the temperature at which drying was done. The relationship between the specific surface of the WAN-dried* fibres and surface tension was very nearly

* Water in the pulp (the pulp had been pressed, but had never been dried) was successively replaced with absolute methanol, chemically dried methanol, chemically dried *n*-hexane or *n*-pentane (for the data cited herein) and freshly distilled *n*-hexane or *n*-pentane; the fibre was then dried. This type of sequence, which is often referred to as 'solvent drying', was dubbed WAN-drying by Merchant because the water (W) is replaced by an alcohol (A), which is replaced by a non-polar (N) hydrocarbon.

linear. When the linear plot was extrapolated to zero surface tension (an admittedly large extrapolation), a specific surface of about 250 m.²/g. was obtained. If the specific surface of the basic cellulosic filaments in the pulp were taken as 340 m.²/g., it would seem that 90 m.²/g. or 26 per cent. of the sites were involved in cross-linking. Accordingly, the number of cross-linking bonds per unit length of the average filament would be $0.26 \times 6.4 \times 10^8 = 1.7 \times 10^8 \text{ cm.}^{-1}$

It will be seen from Fig. 2 that the process of peeling filaments from the fibre should require an energy equivalent to twice that needed for simple bond breaking when the angle θ is small and smaller energies as θ is increased until an angle of 15° or 20° is attained, beyond which the energy is equal to the most ideal value (nU per cm.). If two or more filaments were peeled simultaneously, the effect would be to shift the falling portion of the curve to smaller angles.

The probability of various mechanical actions resulting in the peeling of filaments at various angles would seem to depend upon the force P required at the various angles. The force is easily seen to be $(EA/z)(z' - z)$; on solving equation (1) for z'/z , one can show that —

$$P = Eaf [(1 + 8nU/EAf^2)^{1/2} - 1]/2 \dots\dots\dots(3)$$

This equation reveals a remarkable dependence of P on the angle of peel. Fig. 3, which depicts this relationship, embraces three decades of semi-logarithmic paper; the force varies from 28 microdynes for a backward peel ($\theta=180^\circ$), 55 at 90°, 400 at 30° and a rapid rise through 900 at 20° to 8000 microdynes at 0°. Although the energy requirement for most of the range is sensibly constant, it seems highly likely that most of the peeling away of filaments should occur at large values of θ , that is, backward or sidewise peeling should be the rule.

Although our discussion deliberately invokes some imaginary, highly idealised beating process, it is tempting at this juncture to digress on the possible connection between this theory and the development of sub-microscopic fibrils on the surfaces of fibres. *Fibrage*, as visualised by Sigurd Smith⁽¹⁾ presumably occurs in all beaters, Jordans and other refiners of similar principle. The fibrage should exist on both the flybars and bedplate bars. It is an essential aspect of fibrage that fibres moving with the flybars would be nearly in alignment with the direction of motion and brush past nearly stationary fibres, which are nearly antiparallel to the moving fibres. As a result of the forces of surface friction, backpeeling of filaments and of bundles of filaments (fibrils) should occur. Rough calculations show that quite ordinary pressures (undoubtedly less than that actually existing between the bars) would suffice to provide the needed frictional drag force. Even the fluid

friction drag on long lengths of backward-peeled filaments would provide a significant share of the required peeling force.

Returning to our more general discussion, it seems clear that the most probable modes of peeling are those for which θ is large — certainly large compared with 20° — so that the idealised energy requirement should be of the order of nU per cm. of filament removed. The area released with the breaking of each bond should be twice the area associated with each anhydroglucose unit or $2 \times 8.35 \times 5.12 \times 10^{-16} \text{ cm.}^2 = 8.54 \times 10^{-15} \text{ cm.}^2$ Accordingly, the area of filaments released in the peeling process should be of the order of $8.54 \times 10^{-15} / 3.5 \times 10^{-13} = 0.024 \text{ cm.}^2/\text{erg}$.

Unfortunately, we have, as yet, very little basis for estimating, from experimental data, the surface area developed in a pulp in the form of a sub-microscopic fuzz on the surfaces of the fibres. Merchant's technique has not yet been successfully extended to beaten pulps and there would be some question about the legitimacy of the extrapolative method when applied to evaluate the surface area of microscopic fuzz. The filtration resistance (to water) of beaten woodpulp indicates that the specific surface developed through the production of fibrils by ball milling is roughly $2 \text{ m.}^2/\text{g}$. (intensive milling).⁽¹⁸⁾ A little arithmetic shows that the specific surface of fibres would be increased by only $0.2 \text{ m.}^2/\text{g}$., if all the cellulosic filaments on the surface were each half removed; here, again, we assume that 26 per cent. of the bonding sites were occupied before the partial removal of the filaments. For the purpose of calculating an order of magnitude estimate of the energy required per ton of pulp to produce the sub-microscopic fuzz, we will assume an area development of $1 \text{ m.}^2/\text{g}$.; this leads to an energy requirement of 0.01 kWh./ton , which is only of the order of 0.0025 per cent. of the total energy typically expended in beaters and refiners.

The estimation of an idealised energy requirement for the *loosening* of the internal structure of the fibre is very hard to come by. If, as a guess, 10 per cent. of all possible sites of interfilament bonding are exposed to water in some sort of beating action, the minimum energy requirement would be 0.4 kWh./ton . Here, there is difficulty (at least for the writer) in imagining a most ideal mechanical mode of action for the breaking of cross-linking bonds between the basic cellulosic filaments within the fibre. It would seem that, in general, two kinds of action could result in internal bond breaking — (a) a jostling action, such as would be provided by shear stresses occasioned by direct mechanical action as in beaters and refiners or by impact or by cavitation such as might be produced in sonic or ultrasonic beating and (b) disruptive action such as might be caused by intensive expression of water from

the body of the fibre resulting from the sudden application of very high compressive stress. In either class of action, there will necessarily be an appreciable expenditure of energy through dissipative effects (associated, for example, with internal friction in the fibre and fluid friction occasioned by sudden movement of water within the fibre structure). Accordingly, a realistic estimate of the energy needed to loosen the fibre structure should include a seemingly necessary dissipative term, thus yielding a total energy requirement substantially in excess of 0.4 kWh./ton. It does seem highly unlikely, however, that the dissipative term would be orders of magnitude greater than this figure. (Typical actual energy expenditures in beaters and refiners are of the order of 1000 times larger.)

Fibre cutting can be defined in various idealised ways and by several experimental methods. In the interest of clarity, we shall restrict our discussion of the energy requirement for cutting to the sort of cutting that occurs when the fibre (or what is left of the fibre after fibrils have been detached) is severed by shearing action. It is generally felt that, because of fibrage, cutting in actual beating engines does not occur in the manner of severing a thread with a sharp pair of scissors. However, remaining in the possibly quixotic vein of speculating on idealised mechanical actions, we must now adopt, for the most efficient mode of cutting, a device which would cut fibres by imposing a sharply localised shearing stress. We are then logically driven, in view of the great length of the molecular chains of cellulose, to accept as a basis for calculation the energy required to break the covalent 1,4 - glucosidic bonds, which, according to Mark,⁽⁸⁾ have a dissociation energy of about 80 kc./mole or 5.6×10^{-12} erg/bond. For the purposes of calculating a minimum energy for cutting, we may assume any parallel array of fibres having a uniform cross-section in terms of number of basic cellulosic filaments, in which the fibres are arranged end to end and imagine that the array is cut with planes 1 cm. apart. We further consider that each plane cuts each chain at the nearest glucosidic linkage. The calculated energy requirement then turns out to be the incredibly small value, 2.7×10^{-5} kWh./ton. The cutting mechanism could be quite dull and the energy requirement would undoubtedly remain small compared with, for example, the idealised energy requirement for the production of fibrils. The degree of cutting involved in our calculation is moderate, corresponding to the severing of about one fibre in three in a long-fibred woodpulp. If the ideal cutting energy requirement seems paradoxical, the result can be explained in consideration of the number of bonds broken in comparison with that when filaments are peeled away. The number of glucosidic linkages ruptured per cut of each basic filament is only 105, whereas the number of hydrogen bonds

broken per centimetre length of filament peeled away (taken from the results of calculations presented earlier in this paper) is estimated to be 1.7×10^8 — about one millionfold greater.

The considerations presented in this paper would seem justifiably to lead to the conclusion that a tremendous gap exists between the level of energy now expended in beating and refining and that which would be consumed in nearly ideal processes. The creation of such processes is indeed another problem and, judging by the difficulties encountered in the intelligent and energetic efforts already expended in this area, the problem is an exceedingly formidable one!

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Transcription of Discussion

DISCUSSION

DR. D. ATACK: Some time ago, Dr. W. B. Campbell (*Pulp and Paper Mag. Can.*, 1934, 35 (4), 218) made an estimate of the efficiency of the groundwood process similar in many respects to that given for the beating process by Dr. Van den Akker; both estimates are based on the increase in surface free energy to produce a given kind of pulp as a result of a purely mechanical treatment. Although the surface free energy assumed by Campbell is approximately ten times larger than that calculated by Van den Akker, it is found that, based on the criterion of efficiency —

$$\text{Efficiency} = \frac{\text{Increase of surface free energy to produce an acceptable pulp}}{\text{Total energy input}},$$

both processes are very inefficient. Campbell measured the surface area of a typical acceptable groundwood pulp and Van den Akker has calculated the increase in surface free energy produced by an idealised beating action.

Both authors suggest that not only may improved efficiency result in economy of energy, but also in more suitable pulps. It is implicit in this suggestion that we have a basic understanding of the energy conversion processes associated with the production of a desirable pulp.

Dr. Van den Akker has listed some of the processes of energy dissipation (fluid friction, surface friction and internal friction) and suggests that they may lead to bond breaking and molecular chain slippage in the fibres. He then implies, presumably with good reason, that these processes contribute very little, if at all, to the desired beating action. There are reasons to challenge this viewpoint and I think he would agree that only when we know the nature of these energy conversion processes is it possible to discuss their merits in the beating action. Moreover, if such studies, which are not easy ones to undertake, show that certain processes are undesirable, it is more than likely that methods for their elimination may be suggested from the results of such studies.

Unfortunately, as Dr. Van den Akker points out, the energy transfer spectrum of processes in such a complex machine as an industrial beater is a wide one and severe difficulties may be encountered in the elimination or drastic reduction of certain energy levels from a practical process. Alteration of the time scale of the beating action is a potential field of investigation; drastic changes of this parameter have indicated that for certain grades of pulp greatly improved efficiency may be obtained.

Session 4

To summarise — all our efforts to estimate efficiency on a satisfactory basis should be made in such a manner that the reasons for any lack of efficiency become abundantly clear. Moreover, the results of such efforts should be suggestive of ways of eliminating inefficient processes.

DR. H. F. RANCE: I do not want to comment on the physics of Dr. Van den Akker's paper: I am not competent to do so and I trust him completely and accept his conclusions. I want to make one or two general comments. A lot of us have probably investigated different mechanical beaters and beating machines in our time and have found comparatively little difference in their mechanical efficiencies. This might lead some people to be rather sceptical of Dr. Van den Akker's conclusions.

To offset such scepticism, however, there is a very interesting analogy that one can point to — the operation of an electric lamp. The efficiency of transformation of electricity into light in that lamp is very low, indeed. Apparently, judging by Dr. Van den Akker's paper, it is not as low as that in the beating process, but it is extremely low. Now, there is a lot of money behind the technology of the electric lamp, yet it took many years to find a commercial improvement based on an entirely different kind of method for transforming electricity into light.

There is a warning here, I think, for any representatives of the press or others who may think that Dr. Van den Akker's work is going to lead immediately and quickly to some new beating process that may use up a lot less energy.

It is also worth remembering that the new methods that have been found for transforming electricity into light require considerably higher initial expenditure on the equipment that carries out the transformation.

MR. L. G. COTTRALL: Dr. Van den Akker's conclusions rather confirm the conclusion I put before you yesterday when showing you the sorption curves of Campbell. The almost identical curves for beaten and unbeaten stocks demonstrate, in my view, that proportionally very few bonds are broken in the beating process in spite of the vast differences in the paper produced from the unbeaten compared with that from the beaten stock. This small reduction of bonds by beating confirms the small amount of power required to do the actual beating compared with the total power used in the beating apparatus. This also makes me rather sceptical about the high degrees of increased swelling and water boiling that very many say take place in the beating process.

Second discussion

This difference in power is mainly used up in frictional losses of one form and another. Some time ago, we built up the floors of our beaters so that they came almost level with the first bar of the bedplate and thereby we saved some 20 per cent. of the power consumed by the beater, even allowing for the smaller amount of pulp the beater held because of building up the floor.

During lunch, a friend suggested that a beater was a very good apparatus for determining the mechanical equivalent of heat. If Joule had been employed in a papermill, I do not think he would have had recourse to any laboratory apparatus, but could just have insulated a beater from radiation to obtain a very good approximation to the true figure and the small amount of power used in beating would have merely come in as a small experimental error.

MR. N. C. UNDERWOOD: I should like to ask Dr. Van den Akker whether the fibrils are, to a certain extent, already present when the pulp is first put into the beater and if the very low force he shows in Fig. 3 is quite sufficient to pull them back at a high angle θ , but after a little while these have all gone and the probability of the breaking away of the new fibrils is then quite low. After that, quite large forces, three decades up, are necessary to start fibrils. I wonder, therefore, whether it is possible that the initial rapid change in properties is due to a process such as Dr. Van den Akker describes, acting on fibrils already existing and then the slow process after that is due to new fibrils being torn away more slowly.

DR. J. A. VAN DEN AKKER: I certainly agree with Dr. Atack that a good study should be made of the way energy is dissipated in existing processes for beating. I deliberately avoided existing processes with the idea that, if we did so, we might arrive at what I have called idealised figures that have no connection with existing equipments and mechanisms. I am afraid that, if we try to reach for the stars from the existing processes, we are going to be held back and, if we can somehow make idealised calculations, we can see how far we may go. This is why that was done rather than to try to analyse actual beating processes.

On Dr. Rance's interesting comment that the efficiencies of beaters are quite similar, I would say that commercial and laboratory beaters, excepting such special types as the Lampén mill and the ball mill, are basically of similar forms. Really great improvements in the efficiency of the electric lamp were not made until a completely new type came along — the fluorescent lamp — and, speaking in terms of this analogy, we are looking

forward to the day when we can get away from the Hollander type of beating machine to something now unknown, but much more efficient.

To Mr. Cottrall's interesting observation that a beating machine would be a good device for measuring Joule's equivalent, my question would be — to how many decimal places could we determine it? One could raise the question about the efficiency of modern beating devices — is the inefficiency in the second figure or the third figure? — 99.99 per cent. or 99.9 per cent. or what?

Mr. Underwood has introduced a very interesting idea in relating the early, easy beating of a pulp with the theoretically low force required to remove fibrils when partial fibrillation of the pulp has already occurred. He then raised a question about the more difficult breaking away of fresh fibrils. Although the force required to start the peeling of a fibril may be substantial, the energy may be small and, of course, the energy expenditure is substantial only when the peeling has progressed a certain distance; but the point is that the *force* may have a greater influence on the probability of peeling than the energy — hence Mr. Underwood's theory of the slowing of beating with time.

THE CHAIRMAN: Now we will proceed to Dr. Mason's paper.

DR. W. GALLAY: Dr. Mason is to be congratulated on a very fine piece of work in the development of a technique to measure strengths of webs having consistencies in such very low regions. I was very much interested in his correlation of these data with others that Mr. Lyne and I published several years ago on wet-web strengths for consistencies ranging from about 8 per cent. upwards. There appears no real conflict in our views concerning the basic mechanism, but the following point deserves mention.

He has noted that the interfibre forces are mechanical in nature and has compared them with those pertaining to dry textile fibres. As I noted in my presentation earlier, my concept involves the inclusion of physico-chemical forces, in addition to the ordinary mechanical forces that represent simple entanglement. This is in my view of considerable importance in a unified concept of strength development throughout the course of paper manufacture. I should like to ask Dr. Mason's opinion on this matter.

MR. A. P. TAYLOR: Would Dr. Mason paint his very beautiful experimental lily to the extent of telling us whether the movement of his fibres in the film were the actual movement as the film was taken or whether there was an alteration in time scale?

Second discussion

MR. P. G. SUSSMAN: I have two questions. The first concerns the cohesion of networks under surface tension or other forces. Anyone can make the following experiment. Take two glass plates and press them together under water: they will stick together quite hard. There does not seem to be any 'free' surface involved as there is no change in surface area, only the distance between the plates matters. Sheets of paper, however, do not stick together in this way.

The second point is that Dr. Mason has considered the tensile strengths of networks that were formed, I take it, by random aggregation of fibres. We have carried out some experiments on evening out fibre aggregations. One can even out the fibres in a beaker. I have watched these suspensions or aggregates settle down and become denser: we found that, when they were really even, they settled down much more quickly and formed a much denser final aggregate than did a flocculated fibre suspension. I suggest that the compressive strengths and this speed of settling are at least as important as tensile forces on these fibre aggregates, since papermaking processes on the wire are concerned with the settling down of fibres.

DR. S. G. MASON: In reply, first of all, to Dr. Gallay, I wish to make it clear that in the network and wet-web strength measurements we meant that the interfibre forces are largely frictional. According to modern concepts of friction between solid surfaces, there is adhesion because of intermolecular forces.

All of the ciné film shots were taken at the actual speed at which they occurred.

I am not quite clear about one of the last speaker's questions. I agree that, in sedimenting, a pulp suspension packs under the compression from its own weight and is therefore the reverse of the tension in our network experiments, except that in the latter we took the stress to the point of failure: this does not occur in a sedimentation experiment.

I should like to say a word about the effect of aggregates on network strength. We find it very important to ensure uniform dispersal and we do this by pumping the suspension under conditions of very high microturbulence around and around through the tube carrying the suspension, so that we have what we may consider to be one large floc in the system — that is, one continuous interconnected structure. Without uniform dispersion, we tend to get weak spots, with a resulting high scatter in our measured tensile strengths.