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THE HYDRODYNAMIC BEHAVIOUR OF PAPERMAKING FIBRES

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Abstract

This paper summarises three related investigations — the flow characteristics of pulp suspensions, the strength of dilute fibre networks and the flexibility of individual fibres.

When pulp flows through a circular pipe, three regimes of flow (designated as laminar plug, mixed and turbulent flow) may exist, separated by two transition velocities, which, with relatively long-fibred pulps, are sharply defined. Plug flow is characterised by the development of a fibre-free wall layer whose existence can be demonstrated in several ways. Mixed and turbulent flow involve the breakdown of the fibre network by the turbulent stresses. Relationships between flow properties and concentration and types of pulp are discussed. Pulp suspensions can exhibit the Weissenberg effect, which may be taken as evidence of their visco-elastic nature.

The tensile strength of pulp suspensions at concentrations down to 0.2 per cent. and less is measured by a simple experimental technique. It increases with fibre concentration, fibre length, extent of delignification and of beating. A close correlation is found between the network strength at 0.8 per cent. fibre concentration and the conventional wet-web strength at 15 — 20 per cent. It is concluded *that the networks and wet webs are held together mainly by interfibre friction. The predicted correlation between the static network strength and the friction factor in turbulent flow is shown to exist.*

A method of measuring the flexibility of individual fibres is described. The method is based on a classification of rotational orbits of the fibres in laminar shear and provides a measure of the distribution of fibre flexibility in a given sample. It is shown that flexibility increases with increased fibre length, decreased amount of residual lignin and with beating. By means of a series of measurements on pulps cooked to various yields a correlation is shown between fibre flexibility, network strength and the ability of the fibres to suppress turbulence in water.

Introduction

IN view of the fact that paper is made by subjecting a suspension of fibres in water to various conditions of more or less controlled flow up to the instant when the fibre structure is frozen in the wet paper web, the importance to paper technology of a basic understanding of the behaviour of papermaking fibres in suspensions is obvious. Yet comparatively few investigations have been made in this field, although there are signs that in North America, at least, more research activity may be expected, particularly since the recent formation of the TAPPI Fluid Mechanics Committee to stimulate and support basic research in this field in the universities and research institutes. There are also signs of increased research activity in the industry itself.

For several years at the Pulp and Paper Research Institute of Canada, we have been working on several aspects of the problem and, after some persistence, have succeeded in convincing ourselves that the flow behaviour of pulp suspensions is capable of systematic analysis and is of considerable scientific interest in its own right. Some of this work was described(1) at the 1954 Appleton (U.S.A.) *Symposium on Fundamentals of the Fourdrinier Machine* in the form of a summary of a series of investigations on the characteristic movements and interactions of various types of particles, including fibres, suspended in liquids in laminar shear; this work was designed to provide an understanding of the mechanism of aggregation of pulp fibres under conditions of stable laminar flow. Since then, we have continued and extended our work in various directions.(2-4) It is our object at this time to present a progress report of some of our recent work and particularly to discuss the importance of the formation of fibre network structures upon the macroscopic flow behaviour.

The flow of pulp suspensions

General remarks

The flow of an ordinary (or Newtonian) liquid in a system of specified geometry in response to a specified stress (generally a pressure system) can in theory be predicted from hydrodynamic principles if the density (ρ) and the shear viscosity (μ) of the liquid are known. If the liquid is non-Newtonian and homogeneous, three or more fluid parameters are required, one of which is the density; the others evaluate the apparent viscosity and elasticity and their variation with shear rate.(5-7) Application of hydrodynamic theory requires that the system is homogeneous and that there is continuity of velocity at all points including the boundaries — that is, there is no wall slip.

As will be seen, pulp suspensions at papermaking concentrations usually do not meet these requirements, since they are frequently heterogeneous (because of flocculation) and often show what amounts to wall slip. Consequently, pulp suspensions exhibit flow phenomena that are more complicated than with most fluid systems investigated and indeed show behaviour that is in some respects unique. In the following sections, we will attempt to summarise briefly the general patterns of behaviour that have emerged from our own and related investigations.

Very dilute fibre suspensions

When a suspension so dilute (<0.01 per cent.) that the fibres are isolated from one another, except for occasional collisions, is subjected to laminar shear, the fibres rotate in well-defined orbits and, if flexible, bend; at the same time, they assume a preferred statistical orientation in the direction of flow.(1, 8, 9) An important consequence of rotation is that the effective volume of a fibre exceeds its true volume by a factor r^2, where r is the axis ratio.(1, 8) As the concentration is increased, the fibres form aggregates or flocs as a result of shear-induced collisions and mechanical entanglement. The aggregates are also broken down by shear stresses, so that under certain conditions a reversible (dynamic) equilibrium between floc formation and floc destruction is established in which the state of aggregation is determined by the shear rate.(10)

All the above pertains to suspensions whose concentration lies well below that of papermaking interest. The experiments leading to this picture were conducted for the most part in Couette-type devices in which individual fibres could be studied under conditions of laminar flow. We will discuss one of the techniques in greater detail later in connection with fibre flexibility measurements.

Suspensions at papermaking concentrations

At higher concentrations (upwards of 0.05 per cent.) when interactions play an increasingly important role, it was necessary to resort to other experimental methods. Much of our work has been done with systems in which flow through long precision-bore glass tubes about $\frac{7}{8}$ in. diameter (to correspond roughly to Fourdrinier machine slice openings) was studied by direct observation, by optical scanning and by measuring pressure gradients at various flow velocities.(2-4)

Fig. 1 shows the result obtained when the dimensionless friction factor, f, defined by —

$$f = \frac{\Delta p . D}{2L\rho U^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

(where Δp is the pressure drop due to friction, L and D are the length and diameter of the tube, ρ is the density and U is the bulk velocity) is plotted as a function of U on a log-log scale for an unbeaten softwood pulp suspension. The corresponding curve for pure water is included for comparison. The friction loss curve of the pulp, which is typical of a large number of pulp suspensions, is divided into three parts separated by two transition points (C and D) at which there is a discontinuous change in slope, which serve to identify three separate regimes of flow as follows —

1. *Laminar plug flow* — At low velocities (BC, Fig. 1), a plug flow region exists in which there is no movement of fibres relative to one another and the velocity gradient is confined to a fibre-free water layer at the wall whose thickness decreases as the velocity decreases. At very low velocities (AB), when the wall layer becomes very thin, there is a further flow region characterised by a direct fibre/wall friction, which results in flocs rolling along the wall. In this regime — that is, up to point C — $(\Delta p/L)$ is proportional to $U^{0\cdot25}$.
2. *Mixed flow* — At the first transition point (C), flow in the wall layer becomes unstable and a turbulent annulus is formed around the plug. Further increase in U produces turbulent stresses, which cause progressive disintegration of the plug until it disappears at D. In this regime, $(\Delta p/L)$ is proportional to $U^{1\cdot65}$.
3. *Turbulent flow* — At velocities above the second transition velocity D, the flow is completely turbulent; f is practically independent of U — that is, $(\Delta p/L)$ is proportional to U^2 over a considerable range of U.

The transition velocities can also be determined from the degree of flocculation measured by optical scanning.(2) The degree of flocculation obtained from these experiments is a statistical measure of the optical heterogeneity and represents a composite of (*1*) the dynamic structure in the turbulent layer and (*2*) the structure resulting from earlier states of turbulence that is 'frozen' into a coherent plug. It has been suggested that the degree of dynamic flocculation is related to the scale of turbulence.(4) The mechanisms

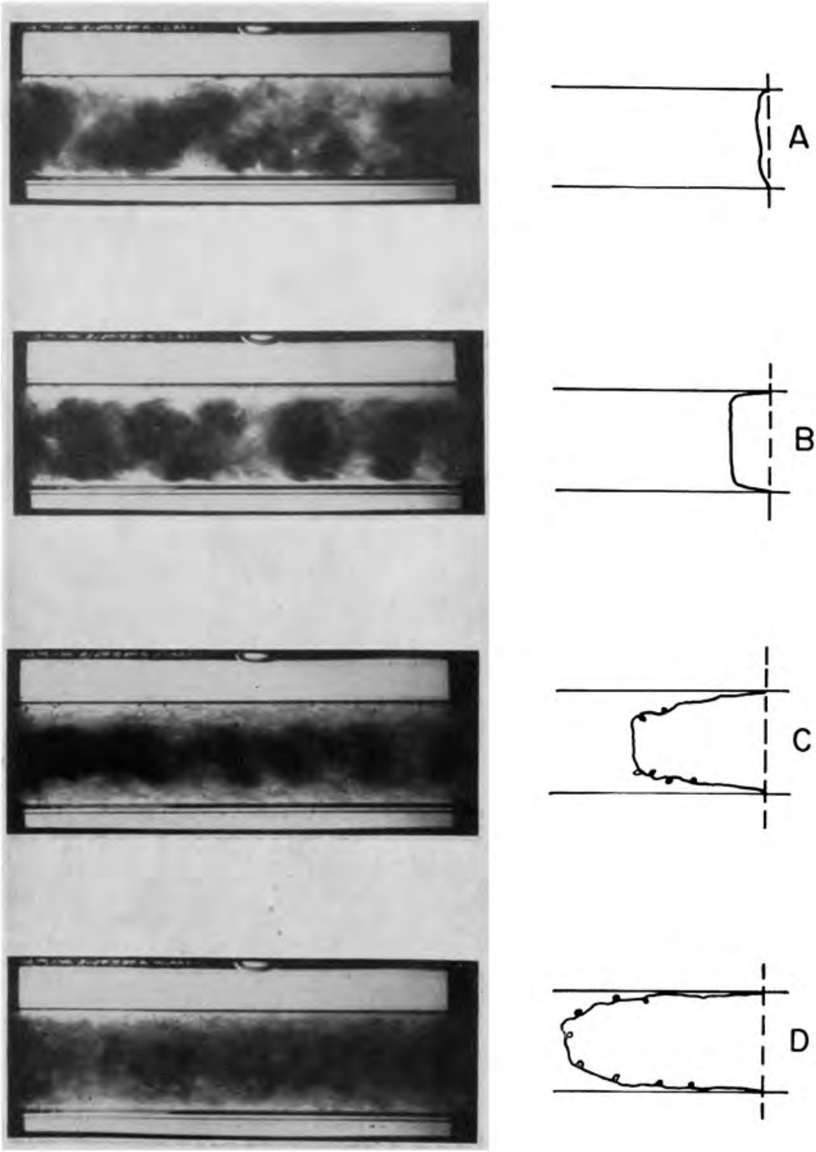


Fig. 2 — High-speed (0.1 millisec.) photographs of the flow of 0.40 per cent. kraft pulp at four velocities —
A — 10 cm./sec. B — 48.5 cm./sec.
C — 126 cm./sec. D — 292 cm./sec.
Long fibres were selected in order to exaggerate the effects for photographic purposes
Impressions of the corresponding velocity profiles are plotted alongside(4)

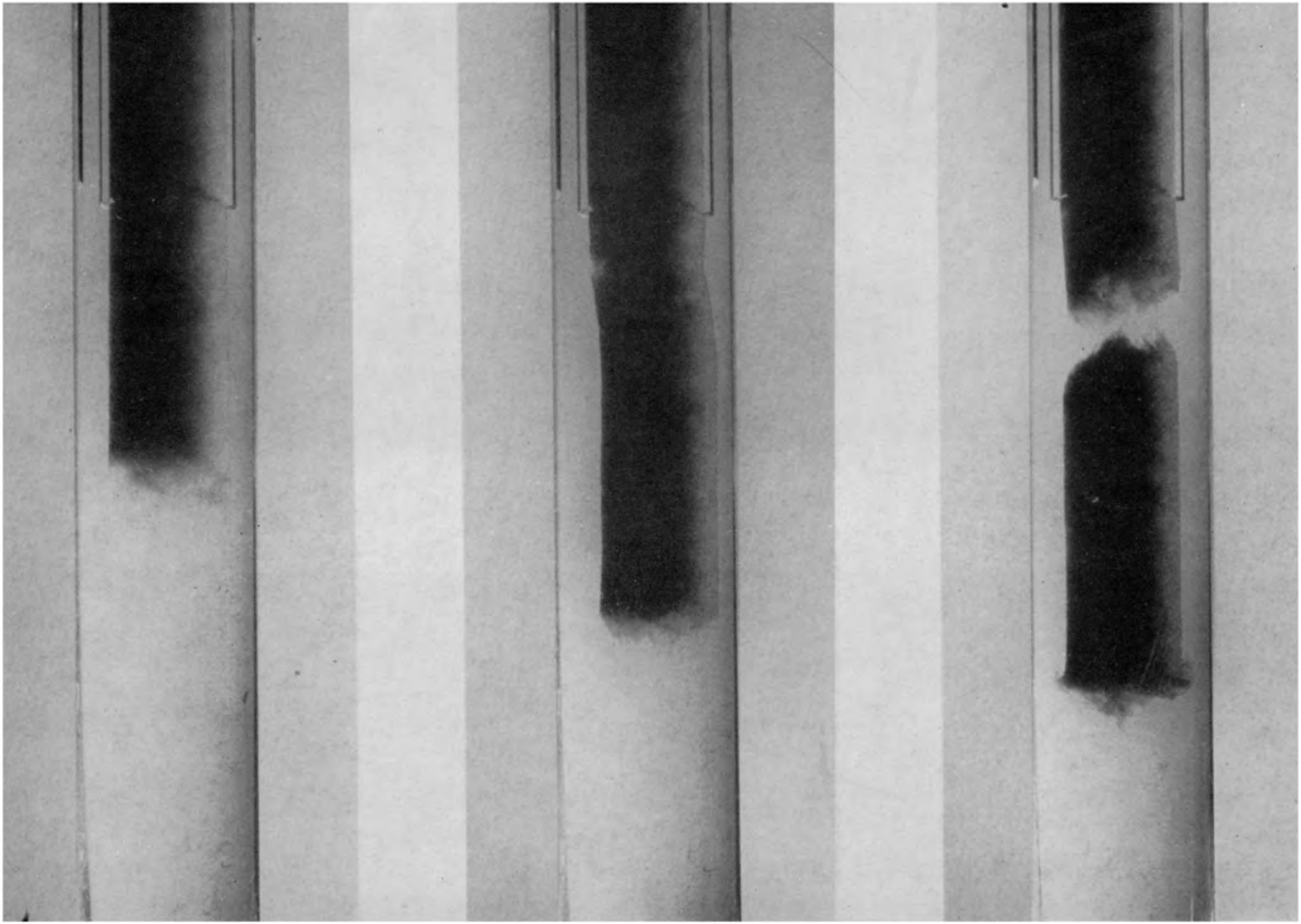


Fig. 9 — Pendant pulp flocs formed during the measurement of network strength

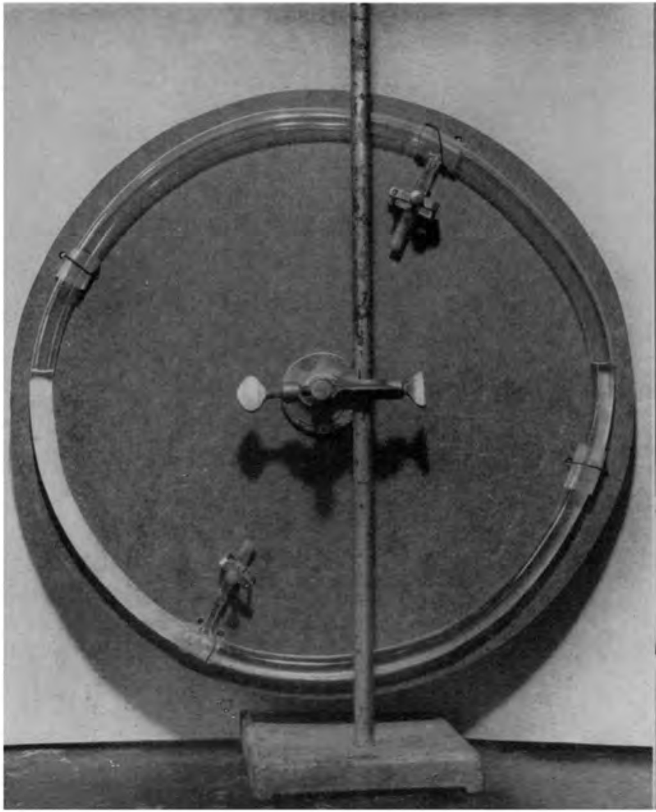


Fig. 4 — Apparatus to show phase separation as a result of plug flow: the tube was rotated counterclockwise

Fig. 15 — Concentric cylinder apparatus for studying particles in sheared suspensions by viewing *X-Y* projection

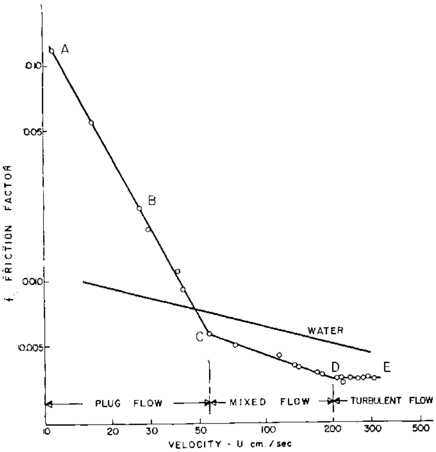


Fig. 1 — The flow curve for an unbeaten softwood sulphite pulp suspension compared with that of water[4] — the fibre concentration was 0.58 per cent.

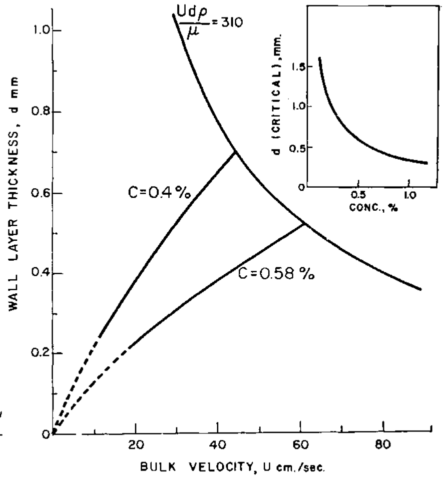


Fig. 5 — The effect of pulp concentration and velocity on the thickness of the laminar wall layer during plug flow

Flow becomes unstable when $Ud\rho/\mu > 310$ — that is, when the two curves intersect

The insert shows the values of d corresponding to this critical Reynolds number as a function of concentration

of flow described above have been confirmed by flash photography (Fig. 2). It is now proposed to discuss certain aspects of each regime of flow.

Laminar plug flow and phase separation — The formation of a fibre-free water layer at the wall by constriction of the fibre network is the dominant feature of this flow regime. Photographs reveal that at zero velocity the layer is absent (that is, the fibres press against the wall) and that the film grows as the velocity is increased and the outside fibres are bent backwards and trail in the stream (Fig. 3). The existence of this film may also be demonstrated by allowing a suspension to run slowly out of a narrow tube; a clear water layer appears below the meniscus due to back-filling of water behind the structure or plug. Assuming a layer thickness d and laminar plug flow, it is readily shown that the volume V_m of water accumulating under the meniscus is approximately —

$$V_m = \frac{2d}{D} V \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where V is the corresponding volume of plug flow.

This evidently is the explanation for the back-filling described in the recent experiments of Johansson and Kubát.(11) We have shown the back-filling effect in a slightly different way by the use of a closed circle of glass tubing, half-filled with pulp suspension and mounted with the plane vertical. Rotation of the tube about its centre produces a rapid and continuous separation with the pulp moving away from the receding meniscus (Fig. 4).

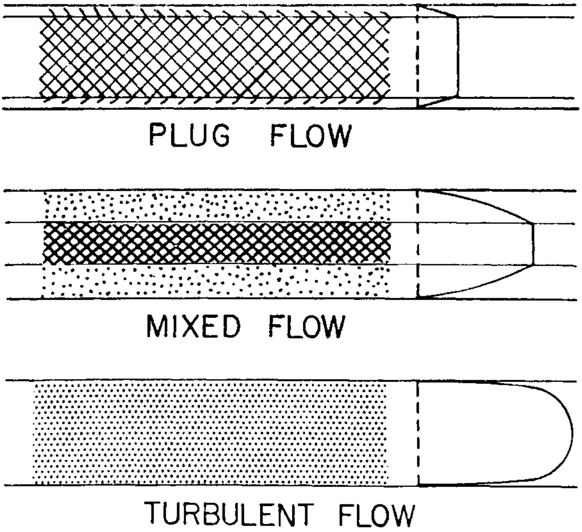


Fig. 3 — Schematic drawings of the three flow mechanisms — note the orientation of fibres near the wall in plug flow and the persistence of the plug in the mixed flow region

It is possible to calculate the growth of the water layer and to predict the velocity at which it becomes turbulent by assuming that the layer is in laminar flow between two parallel planes in relative motion (Fig. 3), one plane corresponding to the wall and the other to the surface of the plug. It is readily shown that the Reynolds number of the layer is given by —

$$R_w = \frac{U_w \rho d}{\mu} \simeq \frac{U \rho d}{\mu} \simeq \frac{2}{f} \dots\dots\dots\dots\dots \quad (3)$$

where U_w is the plug velocity and the other quantities are as previously defined. The critical Reynolds number for this type of Couette flow has been shown(12) theoretically to be of the order of 200 and, in our experiments, to be 300 — 350 for a wide range of μ, U_w and d.

By means of equation (*3*), the mean layer thickness d can be calculated as a function of U from the measured values of f up to the transition velocity, which is considered to occur at $R_w = 310$. This has been done in Fig. 5 for various concentrations of a sulphite pulp. It is seen that the critical wall thickness decreases as the concentration increases and is generally less than the fibre length (*c.* 1.5 mm.).

The mechanism of the formation and growth of the water layer at the wall requires some explanation. Neither the Magnus effect by which Starkey(13) and Tollert(14) explain the motion of particles to the centre of a laminar stream, nor the explanation of a wall layer of low concentration(15, 16) by the absence of particle centres within a particle radius of the wall appear to be applicable in the present case. The first assumes a free particle rotation and the second does not predict a growth of the layer thickness with velocity.

A more plausible explanation is based on the consideration that fibres and flexible fibre structures at the surface are deformed by the flow at the wall and are flattened against the plug as grass is flattened to the ground in a wind. Growth of the layer with increasing velocity may be explained by an increasing deformation of the surface elements, which is further aided by components of the drag on the surface layers that act to compress the plug radially. A concomitant possibility is that the elastic network of fibres (*see* later) is under tension as it flows through the tube; if this tension is developed as postulated by Weissenberg,(7) the network may be elongated in the axial direction and constricted in the radial direction away from the wall. It is evident that the plug is deformed radially by flow, since, on coming to rest, it springs back against the wall. The decrease in layer thickness d (at constant U) with increase in fibre concentration (Fig. 5) is explicable on the basis of network compression.

Mixed and turbulent flow — The mixed flow region, which represents the breakdown of the plug structure due to turbulent stresses in the surrounding annulus, was also investigated by experiments in which the bulk velocity U and the maximum velocity U_m were compared using a dye-injection technique. The ratio U_m/U increased gradually from about 1.03 at the first transition to about 1.18 at the second, both results being reasonable on the basis of the theory of plug flow discussed above and of turbulent flow,(17) respectively.

The turbulent flow regime and at least part of the mixed flow region show friction losses that are lower than those for water in turbulent flow at corresponding velocities (Fig. 1). It is believed that this paradoxical behaviour, which was also reported by Brecht and Heller(18) and earlier workers,(4) is due to suppression of the small scale (or microturbulent) components of the turbulence spectrum by the fibres, which in pure water account for most of the energy dissipation.(19) This inhibition increases with fibre concentration and with the flocculating tendency of the pulp.

The effect of concentration on the flow curves is shown in Fig. 6 and on the first and second transition velocities in Fig. 7. The trends in the data may be shown by extrapolation to be consistent with the observations by other workers using higher concentrations and larger pipes.(4)

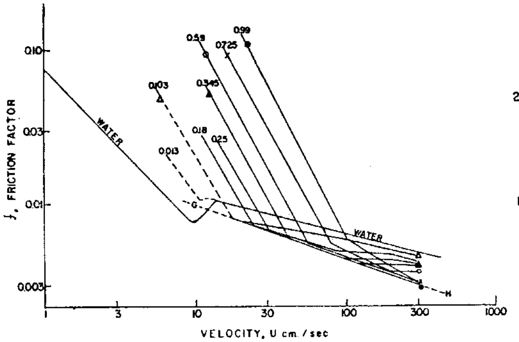


Fig. 6 — Friction factors plotted as a function of velocity for several concentrations of sulphite pulp between 0 and 1 per cent.(4)

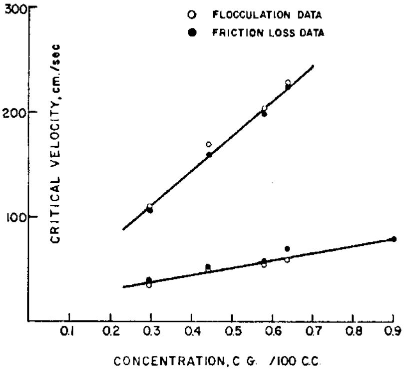


Fig. 7 — The effect of pulp concentration on the transition points. The lower curve (first transition velocity) relates to the onset of turbulence in the wall layer: the upper curve (second transition velocity) indicates the complete disappearance of the plug(3)

Effect of pulp variables

The friction factor curves obtained by us and by others(4, 20) are similar in shape for all pulp suspensions that are capable of forming a coherent network, although the slopes and transition points may vary with the concentration and type of pulp. The index n in the relation $(\Delta p/L) \propto U^n$ shows some variation (1.4 — 1.65) in the mixed flow region and minor variation from 0.25 in the plug flow and from 2 in the turbulent regions. Similar systematic trends are revealed by the flocculation/velocity curves.(3, 4) In other words, the same sequence of flow mechanisms with changing velocity is indicated by the two experimental techniques. We have attempted to correlate the flow behaviour with other pulp properties; however, due to an inherent lack of sensitivity in the measurement of f at high U and appreciable experimental errors at low U (where Δp is low and sedimentation complicates matters), we have thus far met with only limited success.

It is evident that the existence of plug and mixed flows depends on the ability of suspensions to form, by fibre entanglement in ways that have been discussed before,(1, 2, 21) a coherent network that can resist tensile and shear stresses. When the structure is broken down, the flow tends to be turbulent under the conditions of our experiments, although it may be possible for structure breakdown to occur in laminar flow in other flow geometries.

Two other factors considered to be important are the hydrodynamic specific volume α of the fibres (4) and the network compressibility. The former is important, since the concentration parameter should be the hydrodynamic volume concentration αc rather than the mass concentration c. The network compressibility (the volume change under compression) is believed to be of importance in determining the layer thickness d and hence f in the plug flow region: however, independent measurements of these variables are too few to assess their individual importance.

TABLE 1

Turbulent friction factors, network strengths and fibre flexibility

	Pulp sample	*Turbulent f at* 0.4 *per cent.* × 10^3	*Network strength at* 0.8 *per cent., dynes/cm.*^{2}	*Wet web strength at* 13.5 *per cent., metres*	*Rotational orbits*			
					I %	*II* %	*III* %	*IV* %
1	Chopped rayon fibre (10μ diam. × 1.5 mm.)	4.70	0	—	—	—	—	—
2	Groundwood	4.70	0	—	—	—	—	—
3	Douglas fir sulphite 83% yield	4.35	<3	15.3	90	10	0	0
4	Douglas fir sulphite 77% yield	4.30	4.5	26	82	16	2	0
5	Douglas fir sulphite 68% yield	4.10	10.1	51	42	46	12	0
6	Douglas fir sulphite 48% yield	4.00	12.2	79	2	16	70	12
7	Douglas fir sulphite 62% yield	3.95	13.5	51	24	28	46	2
8	Commercial softwood kraft	3.95	—	—	—	—	—	—
9	Commercial softwood sulphite	3.90	15.7	—	—	—	—	—

Experiments with beaten pulps and pulps with varying lignin content clearly indicate that correlation of flow behaviour in the plug flow range with any one of the known pulp properties is not possible. Bleached sulphite pulp, for example, shows a decrease in friction losses with moderate beating, whereas unbleached sulphite and sulphate pulps show an increase or no change.(18) Similarly, high-yield pulps show lower losses than normal pulps, but not in order of their yields. More than one effect appears to be operative. It might be speculated that a variation in the type of pulp or in its preparation, which is accompanied by increased swelling, will not only increase the hydrodynamic volume at a given value of c, but will increase the compressibility through increased flexibility and altered surface conditions. These effects produce opposite effects on the flow resistance and to some degree may be independent.

The most reliable correlations have been observed in the turbulent range. Here, the friction factor f tends to be independent of U and its magnitude is considered to be an inverse measure of the effectiveness of the pulp in suppressing turbulence. Table 1 lists the turbulent friction factor at a constant concentration in decreasing order of f. The samples include a series of Douglas fir sulphite pulps cooked to various yields so as to vary the lignin content and (as will be seen later) the fibre stiffness. The table includes numerical values of the network strength, which is discussed later; the network strengths are in increasing order, confirming that the higher the coherence of the fibre network, the greater the suppression of turbulence and hence the lower f.

Other systems

The flow behaviour of pulp suspensions finds close parallels in the behaviour of other systems — for example, the formation of an oil film at the wall has been suggested to explain the plug flow of greases(22) and a water film to explain the plug flow of clay suspensions.(23) Some polymer solutions show lower turbulent friction losses than does the pure solvent at the same velocity.(24) The phenomenon was attributed to a wall effect suggested by Oldroyd,(25) but Davies(26) suggested that it was due to suppressed turbulence.

The Weissenberg effect

We conclude this part by referring briefly to a property of pulp suspensions that illustrates their visco-elastic behaviour. When fibres are suspended in a viscous medium such as corn syrup (in order to prevent sedimentation and excessive wall slip and to suppress turbulence) and a vertical cylindrical rotor is inserted, the suspension climbs up the rotor to form different profiles as illustrated in Fig. 8. Analogous behaviour is shown when suspensions of very fine filaments of rayon ($<3\mu$ diameter) are sheared in a Couette viscometer; the suspensions climb when the filaments are long enough to undergo elastic bending in the course of their rotations.(27) This phenomenon is commonly observed in visco-elastic gels such as aluminium stearate in benzene and is known as the Weissenberg effect. The effect has been attributed to recoverable elasticity, which causes the development of a system of tangential tension forces in the fluid as it is sheared.(7, 28) These tensions, to use Weissenberg's terminology, 'strangulate' the fluid — that is, the tension tends to be relieved by inward radial flow of the liquid causing the flow observed. In pulp suspensions, it is believed that the effect is associated with elastic deformations, which may be due to deformation of individual fibres or of fibre aggregates by the shear stresses. It should be mentioned that the Weissenberg effect has not yet been related quantitatively to the fundamental rheological properties, although some progress has been reported by Roberts(29) and Ward and Lord(30) using homogeneous gels.

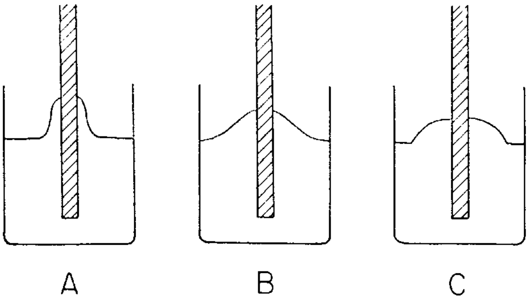


Fig. 8 — Three types of Weissenberg climbing-effect profiles obtained with a rotating rod immersed in a viscous pulp suspension

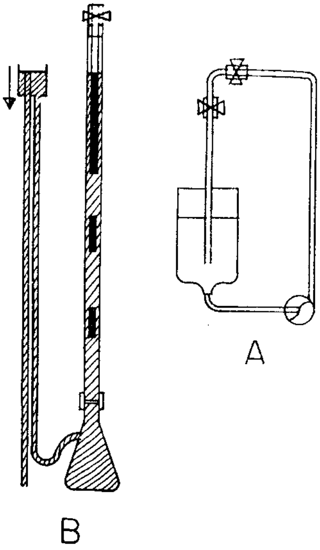


Fig. 10 — Network strength apparatus (schematic)
A — shows the method of forming the floc in the test-tube
B — shows the testing apparatus in operation

Coherent fibre networks

Measurement of network strength

The flow phenomena discussed above indicate that, even at low concentrations of fibre suspensions, interconnecting networks can be formed in which the fibres become interlocked or entangled. The existence of a coherent network can be strikingly demonstrated by allowing a suspension to emerge slowly into water from the lower end of a vertical tube as shown in Fig. 9 so that a pendant rod of fibres is formed, which can support its own (buoyed) weight until a critical length is reached, when it breaks. This simple technique has been used to measure the tensile strength of the network.

To obtain reproducible results, it is important to disperse the fibres in the tube as uniformly as possible. This is done by inserting the tube in a circulating system and pumping the stock as rapidly as possible so that small-scale turbulence is produced. After equilibrium flow is reached, the tube, containing the uniformly dispersed suspension and having its upper end closed by a clamp, is then transferred into a vertical glass tube (Fig. 10) filled with water and the clamp is opened so that the fluid levels in the test-tube and the outer tube become equal. Water is then drained from the outer tube by lowering the constant level device at a constant speed of 1.13 mm./sec. The coherent network runs out of the tube as shown in Fig. 9 into water flowing at the same velocity until it breaks, usually near the tube mouth. The breaking length of a number of such fragments is measured and a mean length (L) is computed.

Precautions must be taken to eliminate air bubbles and to ensure that the suspension and the water are at the same temperature.

Experiments have shown that the breaking length L is independent of tube diameter provided it is large enough to permit uniform dispersion. As might be expected from a visco-elastic system, the breaking length decreases with decreasing flow rate according to the approximate relation—

$$L = aU^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where U is the velocity of flow. For this reason, the velocity was standardised at 1.13 mm./sec. It should be noted that this is the region of plug flow with fibre/wall friction.

Neglecting any changes in dimensions due to elongation of the network, the tensile strength at break is readily shown to be —

$$\tau = cgL\,(1 - \frac{\rho_0}{\rho_1}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where τ is the macroscopic tensile stress (dynes/cm.^{2}), L is the breaking length (cm.), c is the fibre concentration (g/cm.^{3}), ρ_0, ρ_1 are the densities (g./cm.^{3}) of water and the water displacement density of fibres, respectively and g the acceleration of gravity.

Taking $\rho_1 = 1.60$ g/cm.^{3}, this reduces to —

$$\tau = 0.38\ cgL \quad \text{dynes/cm.}^2 \quad \ldots\ldots\ldots\ldots \quad (6)$$

The network strength is probably better expressed as $\tau^1 = \tau/c$, the stress borne by unit mass cross-section of fibre substance, that is —

$$\tau^1 = 0.38\ gL \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

or more simply as L.

Effect of pulp variables

Although still in the exploratory stages, the experiments have revealed a number of items of interest. These may be summarised as follows —

1. *Concentration* — Breaking length L invariably increases with concentration at a rate that is characteristic of the pulp. At high concentrations ($>$ 1 per cent.), reliable values are difficult to obtain, because of increasingly poor fibre dispersion, which creates weak spots in the structure. Fig. 11 shows the variation of L with concentration for pulp beaten to various degrees.
2. *Lignin content* — Pulps prepared from chips cooked to various yields in order to vary the amount of lignin show significant variations in L and τ Fig. 12 shows the change in τ at a standard concentration (0.8 per cent.) of black spruce sulphite pulps, which, incidentally, were given as little refining treatment as possible. Table 1 includes values for the Douglas fir mentioned in the flow experiments. Both pulps exhibit the same trend — increase in L with decrease in yield until an apparent maximum is reached below 60 per cent. yield.
3. *Beating* — Beating appears to increase τ. This is illustrated in Fig. 11 and 13 for the 68 per cent. yield spruce pulp (mentioned above). The pulp was beaten in a Valley laboratory beater with the bedplate load reduced to 1 kg. to reduce fibre cutting.
4. *Fibre length* — Although it is difficult to investigate the effect of varying fibre length alone in pulps, the results obtained from various kinds of pulp — groundwood, short-fibred hardwood and long-fibred softwood pulps indicate that L increases with increasing fibre length.

At first sight, it may appear surprising that a suspension of concentration as low as 0.2 per cent. or less can have a measurable tensile strength, but the simple fact is that the formation of continuous networks at these low concentrations was predicted from considerations of the large increase in effective volume of a fibre resulting from its rod-like shape (mentioned briefly in the preceding section). From earlier experimental evidence,(1, 2) it was concluded that the networks result mainly from mechanical entanglement and, on this basis, it was predicted that the formation of such networks is promoted by increasing the length, the flexibility, the number of hooks and bends, the fibrillation and roughness and the concentration of fibres. As will be seen later, a principal effect in beating and varying yield is to increase flexibility. The network strength measurements reinforce this picture of fibre entanglement.

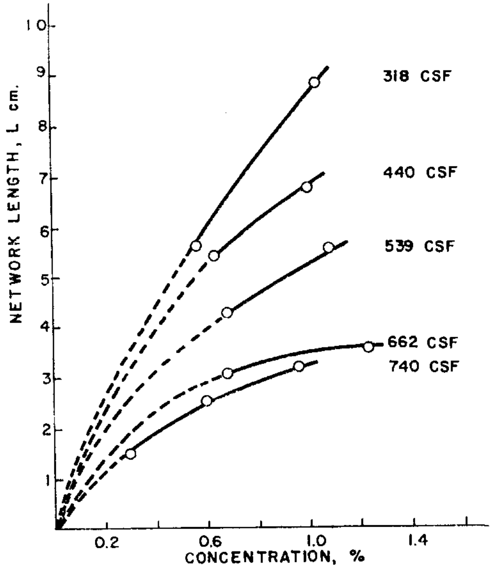
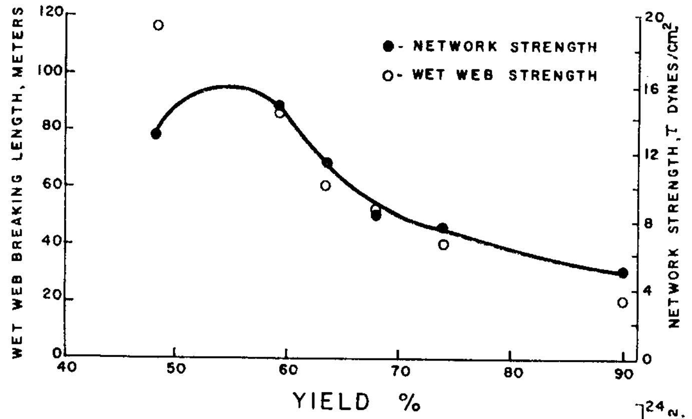


Fig. 11 — Floc length (L) as a function of concentration for samples from a beater run
Pulp — 68 per cent. yield spruce sulphite beaten to various degrees

Wet-web strength

Surprisingly good correlations were obtained between the network strength and the wet-web strength determined on handsheets that were allowed to air dry to various solid contents. Values of the breaking length, calculated in the manner of Lyne and Gallay,(31) are plotted in Fig. 12 and 13 and listed in Table 1. By suitable adjustment of the scales, the wet web and network strengths have been brought almost into coincidence, although a major deviation occurs at the lower yields when the wet-web strength does not show a maximum. It may be considered to be rather remarkable from the correlation in Table 1 that the wet-web tensile strength made at consistencies of 13.5 per cent. can provide a measure of hydrodynamic behaviour at consistencies as low as 0.2 per cent.



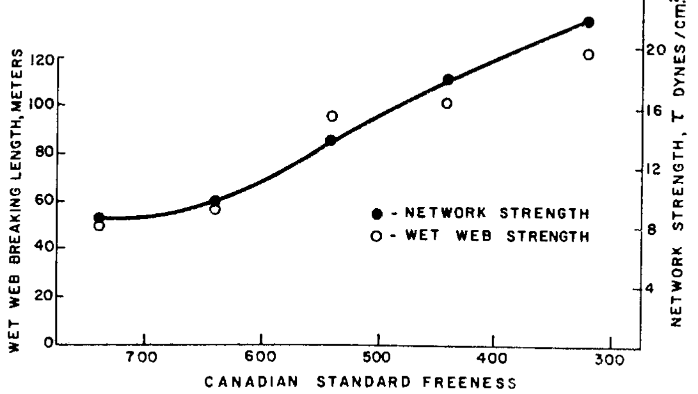


Fig. 12 (*above*)—Network strength (at 0.8 per cent.) and wet-web strength (at 20 per cent.) for samples of spruce sulphite pulp cooked to different yields

Fig. 13 (*below*) — Network strength (at 0.8 per cent.) and wet-web strength (at 20 per cent.) for sample of spruce sulphite (68 per cent. yield) beaten in a laboratory beater

This observation suggests that the same interfibre forces are involved throughout; these forces have been designated *mechanical* and are probably largely fibre/fibre friction as in the felting of dry textile fibres. Lyne and Gallay(31) have emphasised that in wet webs, especially those containing entrained air as in our samples, surface tension forces play a major role in holding the structures together. Since there are no free surfaces and hence no surface tension forces in our fibre networks, there may appear to be a conflict between our views and those of Lyne and Gallay. The conflict is easily resolved, however, by considering the primary forces in both networks and wet webs to be frictional and that the role of surface tension forces in the wet webs is to draw the fibres together and thereby to increase the frictional forces by a factor that is roughly proportional to the surface tension.

Deflocculating agents

Finally, we wish to refer briefly to the effect of additives such as locust bean gum (LBG), which have a pronounced deflocculating effect on flowing pulp suspensions.(2, 4) It has been postulated that gum is deposited on the surface of the fibres and acts as a lubricant, which makes it possible for them to slide over one another with a reduced tendency for mechanical entanglement, that is, with reduced fibre/fibre friction.

In the present experiments, it has been observed that the flocculation of LBG-treated fibres as measured optically was lower in the three flow regions. However, the expected increase in f in the turbulent region could not be clearly demonstrated. In two instances, a small increase was detected and, in two others, there was no change. At the same time, addition of 2 per cent. LBG, based on fibre weight, halved the network strength. The last observation serves to confirm the lubrication theory.

The flexibility of single fibres

General remarks

Finally, we come to a discussion of what may prove to be the most rewarding part of this series of investigations — measurements of the flexibility of single fibres. This work was undertaken as one of a series of studies of the behaviour of various particles, including fibres, suspended in liquids in laminar shear.(1) A study of the bending characteristics of fibres was of particular interest to us, because the work discussed in the preceding parts indicated that increased fibre flexibility may be expected to facilitate fibre entanglement. This should influence network and wet-web properties and, in turn, the hydrodynamic behaviour at papermaking concentrations. The flexibility of fibres is also of interest in connection with the response of fibres to wet pressing, springback, etc., but it is not proposed to discuss these matters here. The work reported is, as far as we are aware, one of the few attempts to correlate the macroscopic properties of pulp suspensions with those of the individual components.

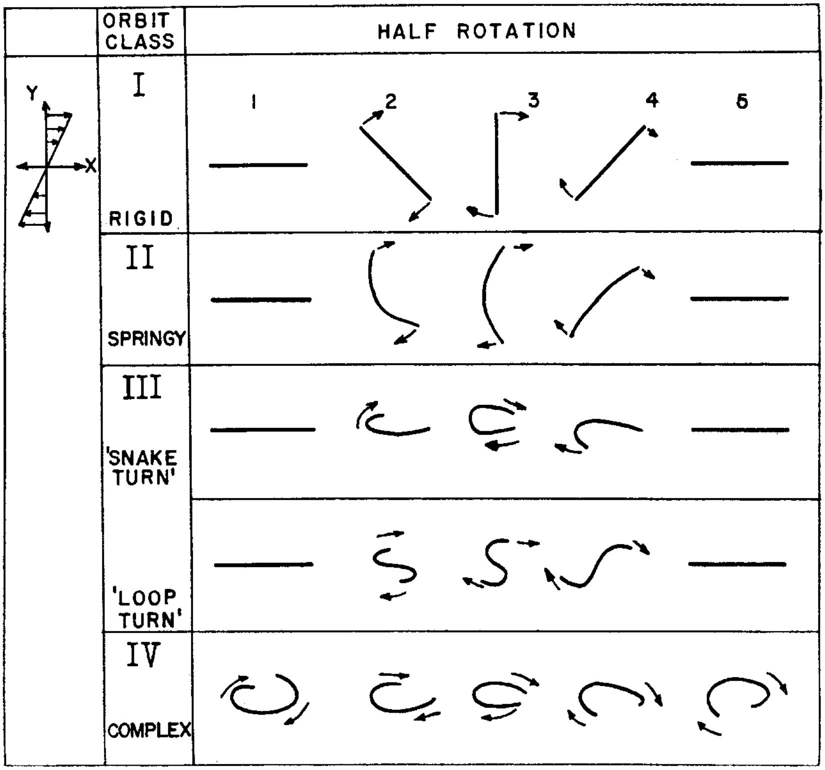


Fig. 14 — Typical rotational orbits of fibres in the X-Y plane
The relation between the co-ordinate system and the shear field is shown in the top left of the figure
Classes I — IV are in increasing order of flexibility

Method

The measurement of flexibility of textile fibres has been discussed by Meredith(32) and recently by Nethercut,(33) but the methods discussed can be used only with long fibres. Seborg and Simmons(34) have described a method for single wood fibres, but the method is exceedingly time-consuming, since the wide distribution of flexibility requires measurements on a large number of individual fibres.

The methods we have adopted make use of the characteristic rotational orbits described by fibres when they are suspended in a liquid subjected to laminar shear as in Fig. 14. The details of these orbits are to be found elsewhere;(1, 9) it is sufficient for our purpose to consider only the most common class of orbits — those in which the principal axis of the fibre lies close to the *X-Y* plane.(9) When the fibre is rigid, it executes a rotation at a variable angular velocity that passes through a minimum when the particle is oriented in the direction of flow (along the *X* axis) and a maximum when at rightangles (along the *Y* axis). The period of rotation *T* is given by Jeffery's modified equation(8) —

$$T = \frac{2\pi r}{G\beta} \quad \dots\dots\dots\dots\dots\dots\dots \quad (8)$$

where r is the axis ratio, G the velocity gradient and β a correction factor that takes into account the shape of the particle. For prolate ellipsoids, $\beta = 1$; while, for straight rigid cylinders, $\beta = 1.4 — 2.0$ for values of r varying 20 — 120, respectively.(8) When the fibre is flexible, it can be caused to bend by the shearing action of the liquid and execute an orbit that is quite different from that of a rigid particle and with a much lower period of rotation and with β as high as 20 or more.

Three methods of measuring flexibility were considered. These involved (*1*) measuring the quantity *TG*, (*2*) studying the relaxation of shear-deformed fibres — the rate at which they straighten when the gradient is suddenly reduced to zero — and (*3*) qualitative observations of the extent of bending during rotation. Since there is a wide spectrum of fibre flexibility in a given sample of pulp because of variations in wall thickness and for other reasons, it was necessary to make measurements on a representative number of fibres, usually about 100. For various reasons, the first two methods were unsuitable, but the third proved practicable and was followed.

Several milligrams of pulp previously fractionated to constant lengths in a fibre length classifier are suspended in household corn syrup, which has a viscosity ($\mu = 60$ poises) high enough to prevent sedimentation. The suspension is placed in the annulus between two coaxial cylinders of a Couette apparatus, in which the cylinders are rotated in opposite directions by independent drives having continuously variable speeds. A single fibre that is exposed to an accurately known velocity gradient can be arrested in the microscope field by adjusting the drives. Two such devices are available and have been described in detail.(35, 36) In one, the microscope is directed normally to the axes of rotation of the Couette cylinders — across the planes of shear and parallel to the *Y* axis (Fig. 14) — while the microscope in the other is directed normally to the *X-Y* plane. Fig. 15 is a photograph of the second apparatus that proved to be the more convenient of the two for flexibility measurements.

To characterise the flexibility, the apparatus is operated at G between 3 sec.$^{-1}$ and 5 sec.$^{-1}$ and the frequency distribution among the following four types of rotation in the X-Y plane is determined, selecting fibres of the required length, using populations of about 100 fibres —

Type I: *Rigid rotation* — The fibres rotate in the manner predicted by Jeffery(8) and remain rigid (Fig. 14, I).

Type II: *Springy rotation* — When aligned in the direction of flow, the particle starts a rigid rotation; on approaching 45°, it bends like a leaf spring and then flicks straight when it approaches 135° and completes the semi-rotation as though rigid (Fig. 14, II). This type of orbit may be considered to be transitional between I and III.

Type III: *Flexible rotation* — The fibre starts out aligned in the X-direction under a tension force that tends to straighten it, one end (the head) starts to bend into a different shear plane with the bend passing as an undulation along the fibre from the head to the trailing end (the tail) until the particle axis has rotated 180° and is again aligned along the X-axis, but pointing in the opposite direction. This was previously called a *snake turn.* (1,9) A less common variation is a *loop turn*(1,9) in which each end forms a head so that the fibre bends into an S-shape (Fig. 14, III).

Type IV: *Complex orbit* — When the fibre is sufficiently flexible, it can undergo a snake turn in which the leading end starts a second half-rotation before the tail completes the first and does not straighten at any time. If sufficiently flexible, a closed loop may form. The complex orbits in this category are distinguishable from III mainly by the fact that the fibre never straightens (Fig. 14, IV).

The classification of orbits according to the four types listed above depends upon the product μG, since the deforming stresses imparted by the fluid are proportional to this parameter. By using a single batch of corn syrup and standardising G, μG was effectively maintained constant at about 300 c.g.s. units. It has been established that water adsorbed by the fibres will, by its plasticising action, increase flexibility. The corn syrup used in the experiments had a constant relative water vapour pressure (R.H.) of 70 per cent.

The fibres are not always uniformly flexible. In some cases, there are regions of the fibre that can be seen to be more flexible than others; in other cases, bending occurs at a hinged joint, presumably caused by localised fracture of the cell wall. Often the joint is a ‘knee-joint’ — that is, bending can occur in one direction, but not in the other.

Following this procedure yielded results that could readily be reproduced to ±5 per cent. in each type of orbit by the same or by different observers. Systematic variation in fibre flexibility caused by various factors such as fibre length, lignin content, beating, etc. could be followed. Some of the salient findings may be summarised below.

Effect of lignin content

As might be expected, it was found that, other things being equal, the flexibility of the fibres increased as more and more lignin is removed. This is illustrated by the results from Douglas fir and black spruce sulphite pulps cooked to various yields that were used in the network strength experiments mentioned previously. Fig. 16 and Table 1 show the distribution of the four types of orbits observed with 2 mm. fibres of Douglas fir. It is seen that, as the yield decreases from 83 per cent. to 48 per cent. — (*i*) the fraction of rigid (Type I) fibres decreases progressively from an initially high value to practically zero, (*ii*) that of the springy (Type II) fibres increases to a maximum near 68 per cent. yield and then diminishes and (*iii*) both fractions of flexible (Type III and Type IV) fibres increase. It is reasonable to assume that increasing the flexibility by one means or another will cause Type III to yield to Type IV orbits. Similar behaviour was shown by black spruce.

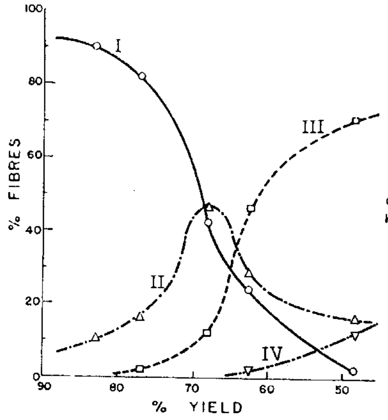


Fig. 16 — The distribution of orbits described by fibres of the 2 mm. fraction of Douglas fir sulphite pulp, as a function of percentage yield
Designations of orbits correspond to those of Fig. 14

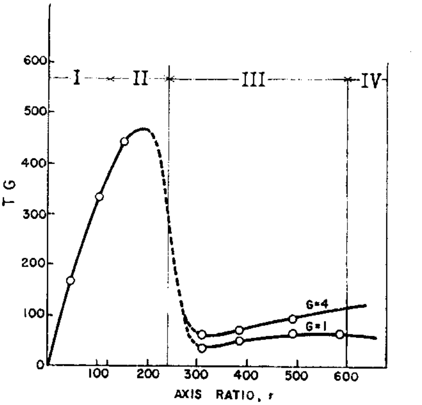


Fig. 17 — The product *TG* graphed against r (axis ratio) for thin (3 μ diam.) rayon filaments: the orbits occurring in regions I — IV correspond to those illustrated in Fig. 14

It should be mentioned that the high-yield pulps were defibred by treatment in a laboratory double disc refiner and, as a consequence, there was some mechanical damage to the fibres that created hinged joints. Fibres having joints were rejected from the sampling, except when it could be seen clearly that they had no influence on the orbit.

Effect of fibre length

Flexibility increases with increase in length. The effect is most easily demonstrated by means of model particles cut from continuous filaments of uniform diameter of rayon and other materials. The effect is illustrated in Fig. 17, where the product *TG* and orbit class are shown as functions of axis ratio. The sharp drop in *TG* in passing from Type II to III orbits, which appears also to be related to permanent deformation, has a number of important consequences in connection with the theory of viscosity of suspensions of rigid and flexible fibres and is discussed elsewhere.(27) The product *TG* was contemplated as a possible quantitative measure of flexibility, but, for reasons mentioned earlier, it was found impracticable with wood fibres.

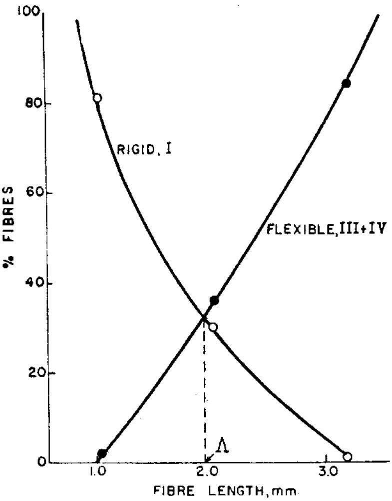


Fig. 18—Orbit distribution as a function of length for 63 per cent. yield spruce sulphite pulp

Λ represents the length at which the fraction of flexible orbits (III + IV) equals the number of rigid orbits (I)

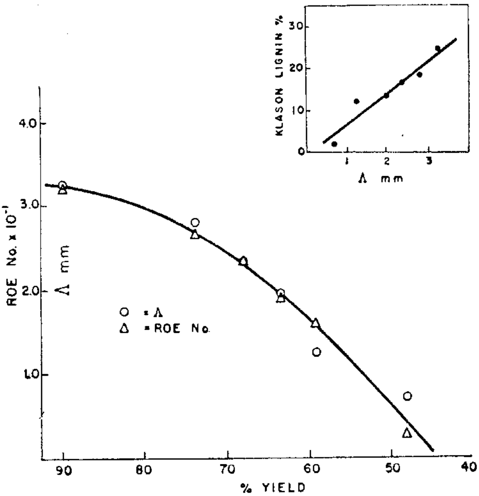


Fig. 19 — Roe chlorine number and Λ plotted against percentage yield for spruce sulphite pulp

Inset — Klason lignin plotted against Λ (*cf.* Fig. 12)

The effect of fibre length can be illustrated in a somewhat different way for wood fibres, using the distribution of orbits on fractionated samples. For simplicity only, two classes of orbit are considered — rigid (Type I) and flexible (Types III plus IV). The distributions are plotted against mean fibre length of fractions in Fig. 18 for one of the variable yield spruce pulps mentioned above. Analysis of curves of this type has suggested the use of

Λ, the length at the point of intersection of the two curves (the length at which there are equal numbers of rigid and flexible fibres) as a statistical parameter describing flexibility; clearly, the smaller Λ, the greater is the mean flexibility. The choice of Λ is not completely arbitrary: it represents the fibre length for any given pulp at which the fraction of fibres having the 'springy' transitional orbit (Type II) is a maximum and at which the greatest heterogeneity of orbits is observed. Fig. 19 shows the variation of Λ with percentage yield for the whole series of spruce pulps. This curve, together with the Roe chlorine number (a measure of the lignin content), clearly shows the increase in flexibility attending the removal of lignin from the fibre. This is also shown by the inset in Fig. 19, where Λ is plotted as a function of the Klason lignin content.

Effect of beating

Generally speaking, beating causes an increase in flexibility, although the data are rather limited and require amplification. The effects can be illustrated by means of the same series of beaten samples considered in the network strength experiments. An effect that was immediately discernible was the rapid increase in the incidence of joints, which probably resulted from localised damage or partial removal of the primary and outer secondary walls as has been described by Emerton.(37) The incidence was so high that fibres with hinged joints could not be ignored as was done with the unbeaten samples, but were included in the sampling.

TABLE 2

Development of flexibility on beating

Valley laboratory beater — 1 kg. load; 2 mm. spruce sulphite fibres

Beating time, min.	*Canadian standard freeness*	*Rotational orbits*				*Hinge-jointed fibres, %*
		I %	*II* %	*III* %	*IV* %	
0	735	38	30	31	1	11
135	620	21	21	56	2	34
240	540	6	13	78	3	41
291	440	2	11	81	6	48
320	320	3	6	78	13	56

The results are summarised in Table 2 and show clearly the increase in flexibility and of the fraction of fibres with joints. This is also shown in Fig. 20, where the distributions of orbits I + II and orbits III + IV have been plotted against freeness. Similar behaviour was shown in another beater experiment, in which the sheet properties were also determined; it was found that the development of burst and tensile strength parallels the develops ment of flexible fibres (orbits III + IV) in a manner similar to the growth of the hydrodynamic specific volume α.(38, 39) In Fig. 21, the growth of flexibility and the incidence of joints is plotted as a function of beating time.

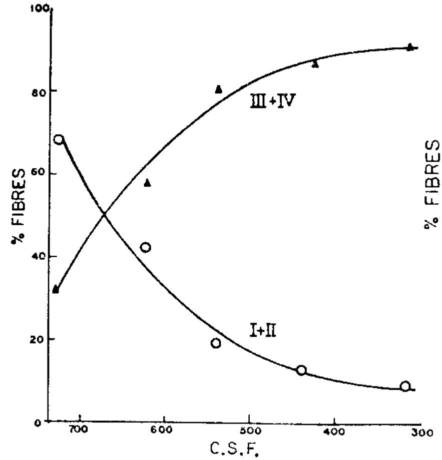


Fig. 20 — Variation in orbit distribution of 2 mm. length fractions with Canadian standard freeness of whole pulp: 68 per cent. yield spruce sulphite pulp beaten in a Valley laboratory beater (*Cf.* Fig. 11 and 13)

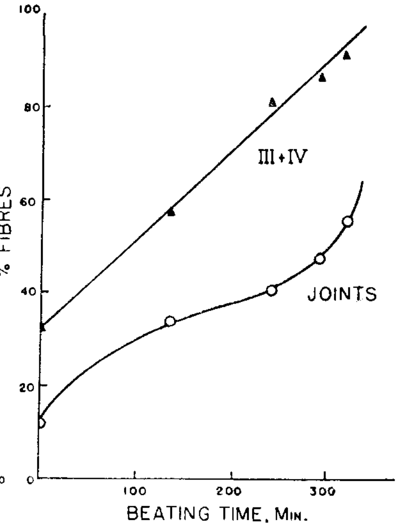


Fig. 21 — Percentage flexible orbits (III + IV) and percentage fibres having one or more hinge-joints as a function of beating time: 68 per cent. yield spruce sulphite pulp

It should be mentioned that, if fibres having joints are omitted from the sampling, a growth in flexibility on beating is still observed; here, the increase is particularly marked in the early stages of beating before the onset of wall damage. It appears also that the development by beating of joints in thin-walled (springwood) fibres is more rapid than in thick-walled (summerwood) fibres, but further work is required before speculating on the significance of this and other observations on jointed and uniformly flexible fibres.

It is clear, however, that this technique of examining individual fibres may be of considerable value in studying the effects of beating and other treatments on the macroscopic behaviour of pulp suspensions and their papermaking properties.

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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 —

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

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.

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.

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 physicochemical 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?

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.