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DYNAMICS OF SHEET FORMATION ON THE FOURDRINIER MACHINE

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Synopsis

The course of the papermaking process, as it occurs on a Fourdrinier machine, is analysed to illustrate how each functional operation performed by the machine influences the final product. The analysis starts with the role played by the slice and its approaches and special emphasis is given to the many compromising factors that determine holey roll design and behaviour. The effect of slice design on orientation, flocculation and jet delivery is also considered. It is shown that the concept of a fibre network structure for the stock with a strength that varies with fibre consistency, length and type explains many of the observations.

The distinction between macro- and micro-formation is defined and the relative effects of the head box and table suction on these properties are illustrated. It is concluded that gross relative motion of stock on the wire is detrimental to macro-formation, but that short range relative motion is beneficial to micro-formation and results in a more uniform fibre distribution than is possible by random turbulent diffusion processes in the head box alone.

The variation of sheet properties across the sheet thickness are discussed and it is concluded that selective filtration that occurs during the forming operation is the principal cause, not the backwashing of the sheet by inflow of water at table rolls, as is frequently reported.

A brief speculation on the construction of the 'idealised' machine-made paper sheet is presented.

La dynamique de la formation de la feuille sur table plate

On analyse le procédé de fabrication du papier sur une machine à table plate pour faire ressortir l'influence sur le résultat de chaque opération.

L'analyse indique d'abord les rôles de la règle ou de la lèvre et des canalisations en amont de celles-ci. On note spécialement les facteurs complexes qui déterminent le dessin et le fonctionnement du rouleau émattonneur. On étudie également l'effet du dessin de la règle ou de la lèvre sur l'orientation de fibres, sur la flocculation et sur le débit.

Beaucoup des observations s'expliquent en envisageant un réseau de fibres offrant une résistance à la déformation qui dépend de la longueur et du type des fibres et de leur concentration.

On distingue entre une 'macro-' et une 'micro-formation' et on indique les influences sur ces propriétés de la boîte de tête et de la table.

On conclut que la 'macro-formation' est entravée par de gros mouvements entre elles des fibres sur la toile mais que la 'micro-formation' est améliorée par de petits mouvements des fibres. Ces petits mouvements entraînent une distribution des fibres qui est plus uniforme que celle produite par les phénomènes de diffusion turbulente dans la boîte de tête agissant seuls.

On traite de la variation des propriétés à travers l'épaisseur de la feuille et on en conclut que la cause principale de cette variation est la filtration selective qui se produit pendant la formation et non pas le 'lavage' de la feuille produit par l'eau qui remonte à travers la toile derrière les pontuseaux—théorie souvent avancée.

On traite brièvement d'une structure idéale pour la feuille faite sur machine.

Die Dynamik der Blattbildung auf der Langsiebmaschine

Es wurde die Blattbildung auf dem Langsieb im Hinblick auf die Beeinflussung des Endproduktes analysiert, wobei man von der Auswirkung der Lochwalzen und Stoffauslaufkonstruktion auf Orientierung, Flockenbildung und Ausfluss ausging. Es konnte gezeigt werden, dass die Festigkeit der Fasernetzwerkstruktur mit Stoffdichte, Länge und Typ der Fasern variiert. Der Unterschied zwischen Makro- und Mikroformation wurde definiert und deren Abhängigkeit von Stoffauflauf und Registerpartie dargelegt. Grobe relative Stoffbewegungen auf dem Sieb beeinflussen die Makroformation negativ, während kleinflächige Formationen die Mikroformation begünstigen und zu einer gleichmässigeren Faserverteilung führen, als es bei unorientierter turbulenter Diffusion im Stoffauflauf allein möglich ist. Als Hauptursache für die Veränderung der Bahneigenschaften durch die Blattdicke hindurch wurde die selektive

Filtration erkannt, die während der Blattbildung vor sich geht und nicht die Auswaschwirkung der Registerwalzen wie es häufig berichtet wurde. Abschliessend wurde die Struktur eines 'idealisierten' auf der Papiermaschine gemachten Papières behandelt.

Introduction

THE relative spatial arrangement of the fibres in a Fourdrinier-made sheet of paper is very largely determined between the head box slice and the end of the forming table. Within this space, the orientation of the fibres, their degree of agglomeration, the relative distribution of materials through the thickness of the sheet and the macro- and micro-mass distribution in the plane of the sheet are all laid down. The subsequent wet pressing and drying of the sheet produce some micro-rearrangement and consolidation of the web, but these operations will not concern us in this paper.

The standard laboratory-made sheet of paper usually represents the most uniform arrangement of the fibres possible from a given sample of pulp. Such a sheet is therefore often regarded as a standard against which the excellence of a machine-made paper may be judged. The laboratory sheet-forming conditions are characterised by extreme dilution, thorough mixing of the fibres, decay of turbulence before drainage, slow vertical drainage with very little relative motion in the plane of the forming wire and a wire mesh sufficiently fine to ensure practically complete retention. Even under such ideal conditions, some pulps prove difficult to form uniformly. The conditions on the average Fourdrinier machine are very different in every respect. Extrapolation from laboratory to production machine therefore requires an understanding of the factors operating during these dissimilar conditions of formation.

The most characteristic property of suspended particles with a high length-to-breadth ratio is the phenomenon of mutual interaction of the individual particles under conditions of fluid shear. These interactions occur to such a degree, even at very dilute concentrations, that the behaviour of the suspension differs appreciably from that of the suspending liquid. The concentrations used in laboratory sheetmaking are purposely held well below the critical value at which these interactions become significant and, consequently, the result of fibre interaction on sheet formation is minimised. The properties of a machine-made sheet, by contrast, reflect the results of these interactions, also of the dynamics of the sheetforming process. Occasionally, they may affect the properties of the sheet to an even greater degree than the physical properties of the individual pulp fibres themselves.

It is the intent of this paper to examine some of the phases of the sheetforming process on a Fourdrinier machine with a special reference to the influence that they exert on the finished product. Since the flow behaviour of the pulp suspension up to and in the head box is being considered elsewhere in this meeting,[1] this paper starts with a consideration of the slice.

The slice

THE head box slice serves the following functions on the Fourdrinier papermachine —

1. A metering gate to control the mass distribution across the machine.
2. A constricting orifice to the flow in the head box to raise the velocity of the diverging jet close to that of the forming wire.
3. A compensating control for distribution deficiencies in the head box proper.
4. A control to provide temporary relief for such operating problems as incorrect roll crowns, plugged felts, dryer ventilation deficiencies, etc.
5. To control the angle and line of impact of the jet on the wire. (These together determine whether there will be pressure drainage or no, breast roll drainage or no, etc. and often control means are provided to change from one arrangement to another during operation.)
6. To control the turbulent content of the discharge (in conjunction with one or more closely associated devices).
7. To control the orientation of the fibres in the jet.

Variation of the slice opening across the machine is the papermaker's method of controlling the average cross-directional basis weight profile. The author and others[2,20] have measured the slice opening and basis weight profiles during operation and correlated the two. As expected, a highly significant point-to-point correlation is found. A coefficient typical of one high speed newsprint machine is 0.5. This is not the full measure of correlation between the two, however, for, as every papermaker knows, the effect of an adjustment to the slice at one point usually produces a change over a wider area of the machine.

Sometimes, the slice must be used to compensate for non-uniform velocities approaching the slice. For example, on a head box with several high velocity inlets, the individual streams may not be completely diffused on reaching the slice and heavy streaks result in line with each inlet. The slice is usually adjusted in an attempt to spread these flows more evenly, but never with complete success. Whenever an excess flow approaches the slice, there is a cross-flow set up towards those parts deficient in flow. The combination of flow across the slice pond plate with the accelerating flow into the slice produces vortices that are drawn down and out through the slice.[3] On the wire, these vortices become unstable, producing weight variations by mechanisms to be discussed in a later section. Improved head box distribution is the correct solution for this problem.

The control of the slice angle is very largely determined by the slice geometry. A study of some of the relevant parameters has been reported by Nelson.[4] Fig. 1 is constructed from his data. Nelson proposes that the angle β, which the jet makes with the horizontal, is determined by the relationship —

$$\beta = f\left(\frac{V^2}{gb}, \frac{Vb}{\mu/\rho}, \frac{B}{b}, \frac{L}{b}, \alpha, \theta\right) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where V = slice jet velocity,

α = angle of convergence of nozzle,

μ = viscosity of fluid,

ρ = density of fluid,

and the other terms are defined in Fig. 1. He argues that in a practical case the effects of the Froude and the Reynolds numbers (the first two groups) are secondary, that the influence of θ is additive and that β is sensitive to B/b only for values close to unity in combination with low values of L/b.

Nelson studied only one value of α; experience with an angle of smaller value and one of 90° confirms a similar relationship to exist and, in particular, the transition to a zone of low sensitivity to occur in the range $1 < L/b < 2$. Thus, the relationship $\beta = \theta + f_1\,(L/b)$, shown in Fig. 1, is a useful approximation for use in practical problems.

The angle of the jet's trajectory is increased in flight by gravity, the amount being readily calculable. The effect that the angle of impingement of the jet on the wire has on the product will be discussed in a later section. Two factors not considered by Nelson are the effects of appreciable variation in the vertical velocity profile of the approaching flow and the ability of the air or water carried round by the breast roll to deflect the jet in flight. These factors will change the relationship slightly, but do not alter its general shape.

Slice designs range the whole gamut from vertical slices to near parallel nozzles and are usually closely associated with a flow conditioning device just ahead of them in the head box. This device might be a secondary slice (on slow, fine machines), one or more holey rolls (on many general purpose machines) or a nest of flow guiding vanes and cross tie rods (on certain newsprint machines). The functions of these devices are to reduce crossflows and to add a sufficient degree of agitation to break up the fibre flocs prior to discharge through the slice. To the extent that these devices pass or themselves create turbulent motion in the flow, they can materially influence the flow patterns that develop over the forming table.

Guide vanes produce narrow boundary layer streaks of low consistency and reduced velocity, which are not completely eliminated by diffusion over the table and the basis weight is reduced in the wake of the vanes by several per cent as a result. Use has been made in several such installations of the

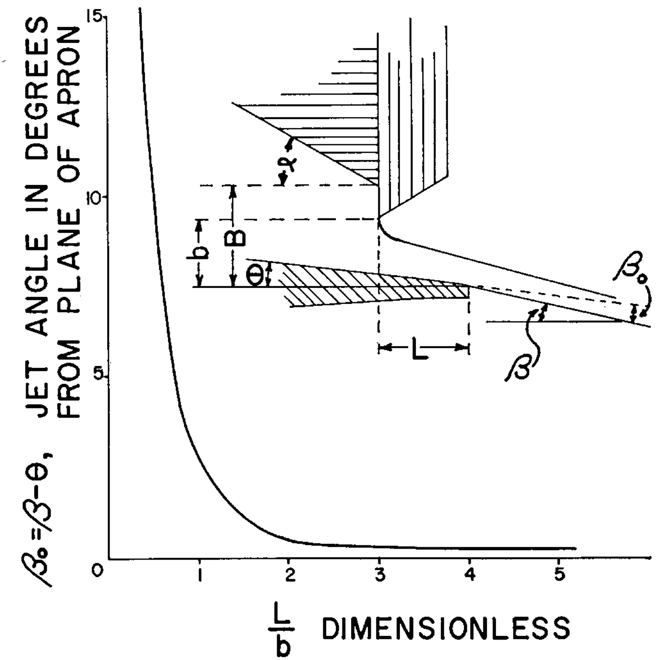


Fig. 1—Relationship between jet angle and slice setting (Nelson)[4]

Karman vortex trail shed from a stationary cylinder placed in the stream between flow plates and slice to increase the diffusion process at the forming table.[5] Burkhard and Wrist found that the relationship between Strouhal number and Reynolds number in this application exhibited the same features as that for the case of flow of water past a cylinder in a deep channel and they selected the dimensions and geometry to ensure a high frequency of discharge, preferably in the aperiodic zone and placed the rod at a point sufficiently distant from the slice to permit diffusion of the vortices throughout the jet before emergence on to the wire (Fig. 2). An alternative arrangement they proposed consisted of turbulence shedding projections on the walls of the approach channel and this arrangement was found in practice to have a considerably less disruptive effect on the jet than the centrally positioned rod at the same energy input.

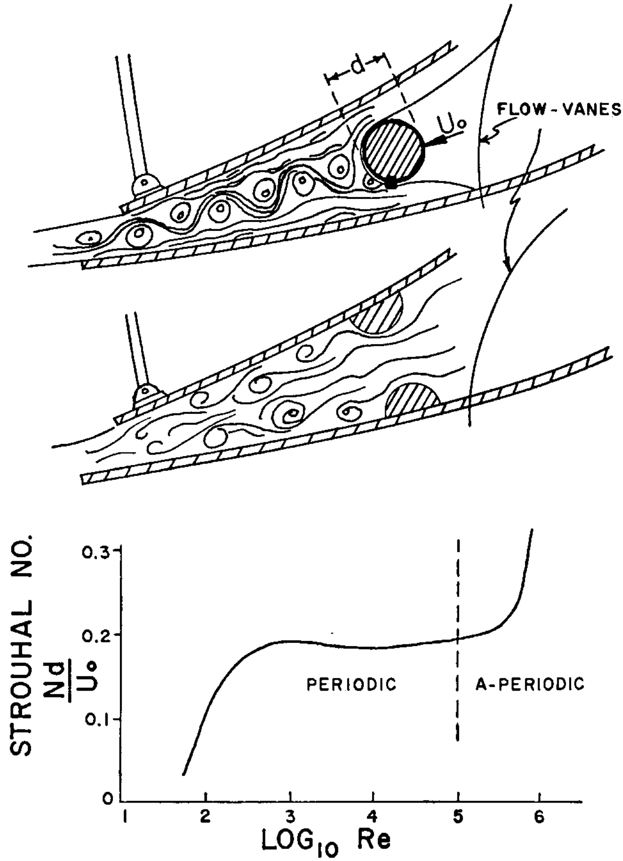


Fig. 2—Turbulence generating rod in slice with flow vanes[5]

The functions of holey rolls in head box slices have been discussed by van de Meer[3] and Mardon[6] and each proposed a different formula for the positioning of the slice roll for different machine speeds and roll design. Although undoubtedly based on experimental findings, neither author has detailed the conditions under which his formula was derived. A paper by

Bennett[7] presented a series of velocity and turbulence results obtained in an air tunnel with a variety of rod rolls, perforated plates and perforated rolls. Factors studied were solidity ratio, grid parameters and roll rotation. All of these authors have treated the problem of the perforated or holey roll as being a special case of a perforated screen with a self-cleaning feature.

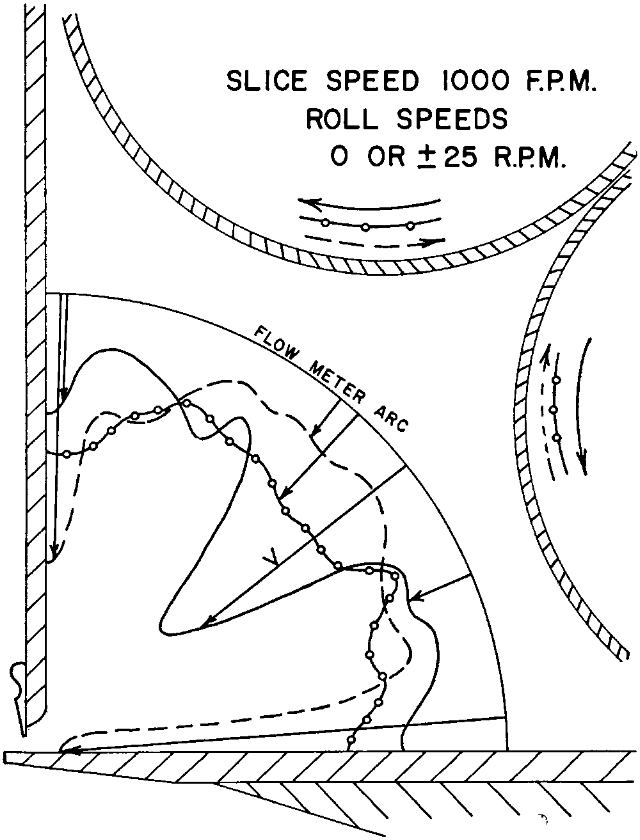


Fig. 3—Flow distribution in region of slice holey rolls

Mardon and van de Meer both stated that the speed and direction of rotation had little effect on the flow.

When a holey roll is placed too close to the slice or the machine speed is raised above the design speed of the holey roll, the slice jet becomes very streaky. A study of holey roll streaks by Wrist, Jordansson and Fisher offers some insight into the mechanism of their formation. Their study was concerned with a vertical slice and two slice holey rolls arranged as in Fig. 3. Production experience with two rolls having 50 per cent open area and $1\frac{1}{8}$ in holes showed that satisfactory quality occurred at speeds up to 10–1 100 ft/min. At speeds above this, holey roll streaks became increasingly apparent in the jet and these became basis weight streaks in the paper. Velocity traverses across the slice failed to reveal a non-uniform velocity profile of periodicity equal to that of the streaks; in fact, velocity traces at all points across the box showed the same mean value and a similar degree of turbulence. This turbulence was a very small percentage of the mean flow, but did increase with speed and was sensitive to roll rotation speed and direction. Flowmeter traverses along an arc between rolls and slice were made with the rolls stationary and rotating. Very close to the roll, the velocity profile across the box reflected the hole spacing, but beyond 2 in from the roll, it was barely evident. In no case was the velocity profile constant along the arc (Fig. 3). It will be seen that the flow pattern is very similar to that past solid cylinders and that rotation produced high velocities in the area of the gap or gaps at which the roll surfaces are moving toward the slice as predicted by hydrodynamic metering theory. There is considerable flow in and out of the rolls in the vicinity of the nip, resulting from the pressure and suction zones associated with the nip of a rotating metering roll; otherwise, the flow through the roll is low. The situation is therefore very different from that of flow through a perforated plate. This finding answered one of the questions puzzling us—why the streak spacing corresponded to that of holes along a single row and not to half this distance as we expected (alternate rows were offset by half spacing). Thus, the turbulent pattern reflected in the jet came from one row of holes on each roll, that passing closest to the other roll or to the wall (according to the direction of rotation) and not from flow through the greater part of the roll. The flow patterns around and through the rolls were studied further by ciné film taken of stock flowing through a full-size sectional model. Fig. 4 is a still taken from this film.

An unexpected finding from this study was the formation of stock lumps in a very systematic manner. We had expected that lumps might form randomly over the roll, would take several revolutions to build up and then discharge randomly. Instead, we found they form within a few degrees travel around the roll and shed in unison across the face of the roll. Fig. 5 illustrates how this occurs.

Another surprise was the ability of these flocs to remain intact right out to the slice. With long-fibred pulp, the hole size and speed of roll rotation has a profound effect on the flow within the rolls, also on the flocculation in the jet. At low speeds of rotation, flow through the roll is slow and circulation within the roll is small. Gross flocculation results: within each roll a continuous rolling 'sausage'-shaped floc was formed, which added and shed off smaller flocs continuously. The fibre floc network strength and the hole size were the controlling factors. The smaller the hole, the larger the flocculation within the roll. Under these circumstances, we were driven to

Fig. 4—Still photograph showing formation of lumps by holey rolls

question the justification for the rolls, since the stock leaving the rolls was more flocculated than that approaching them. We found that a rod or stave-roll was a more effective deflocculator, though, for reasons discussed below, this was not a practical solution. As roll speed increased, circulation within the rolls increased until eventually the network was destroyed and the jet became less flocculated; however, it became increasingly unstable and the solution of one problem had created another even more severe.

The floc formation described above is not the explanation of the weight streaks in the paper, although the flocs so formed may be found lying within these streaks in the paper. It is instructive, however, as illustrating a factor that is very important in the choice of holey roll design and one that, in general, runs contrary to the desiderata of the hydrodynamic considerations for turbulence and jet stability.

It was concluded from the pitot tube traverses that in this instance the streaks that were visible in the jet resulted not from a non-uniform average velocity profile, but from the transverse velocity components of the turbulence

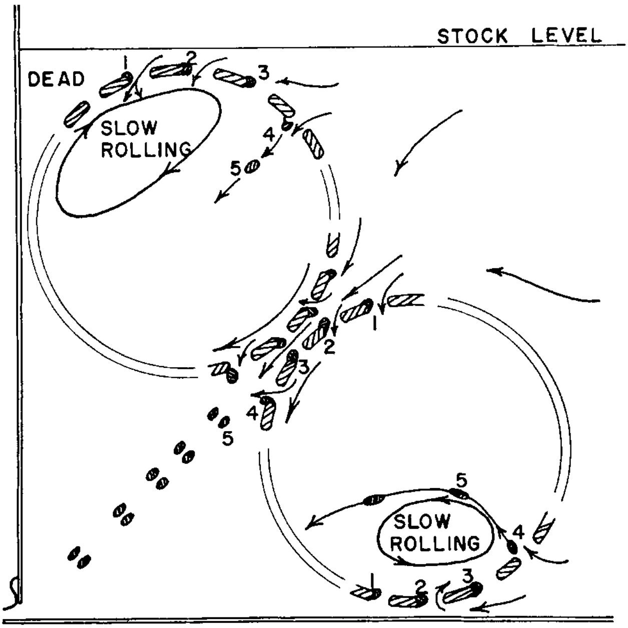


Fig. 5—Sketch showing lump forming process on holey rolls

created by the rolls causing cross-flows within the jets. Even at a distance from the slice at which the streaks were developed, velocity traverses did not show variations in the mean velocity level corresponding to the streak pattern. An 'impact rod' gauge was developed to characterise the jets (Fig. 6). A short piece of $\frac{1}{8}$ in rod was mounted on the end of a leaf spring. The rod extended completely through the jet at a distance 5 in from the slice at which distance the streaks were well established. The upper end of the spring was firmly clamped. The rod could be traversed across the jet, but was used mostly in a stationary position as the streaks themselves moved back and forth across the rod. Two strain gauges cemented to the spring were used to indicate its position. By experimentation with various springs a combination was found that was stiff enough to avoid excessive movement of the rod as the thickness of the jet hitting it (and therefore the drag force) varied, yet was sensitive enough to follow the changes. The final device was approximately critically damped. The strain gauge signal was amplified and recorded by one galvanometer. The non-steady portion of the signal was

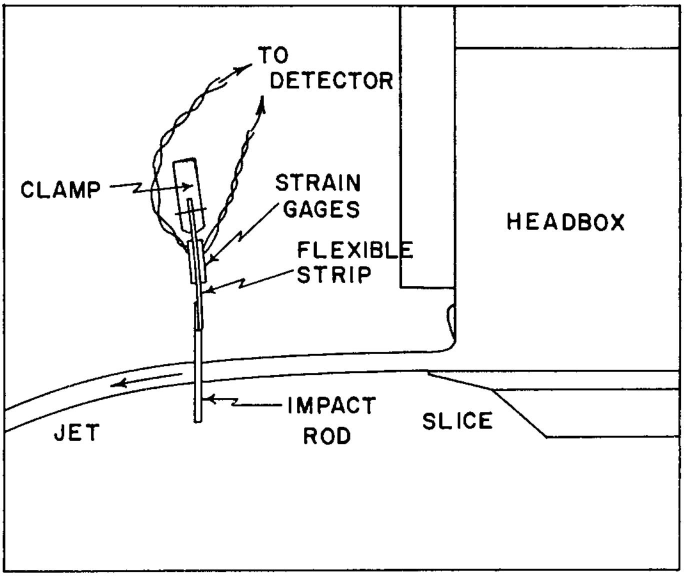
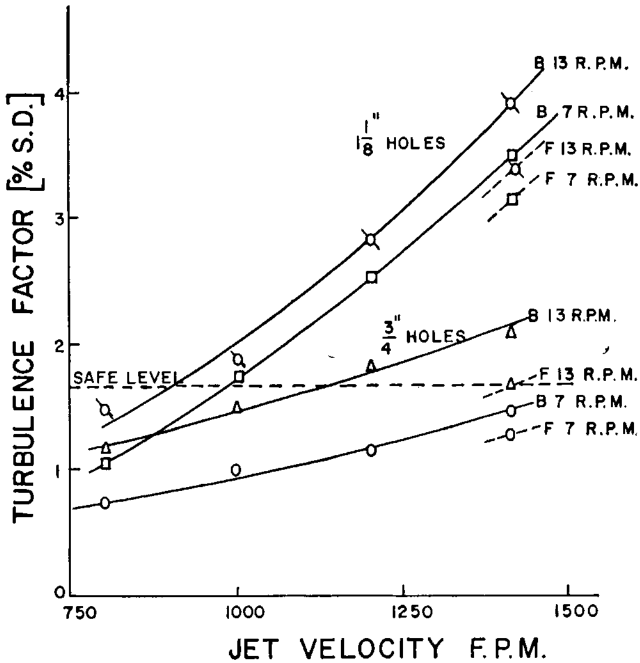


Fig. 6—Impact gauge in slice jet

filtered off, amplified further, rectified and recorded by a second galvanometer. The mean signal varied as the square of the jet speed and was independent of the turbulence level. The non-steady signal varied with the turbulence level and paralleled a visual rating of the jet. A *turbulence factor* was defined as the ratio of the root mean square value of the non-steady portion and the mean value expressed as a percentage. It is proportional to the percentage variation in jet thickness at the point of measurement. The numerical value of the factor increases with the distance from the slice, but, since it does so in a similar manner for all jets, a basis for comparative evaluation was established at the 5 in distance point. This location avoided the difficulties encountered at greater distances with very streaky jets that disintegrated, also is close to a typical slice to wire distance.

Fig. 7 illustrates the effect of jet velocity, hole size and speed of rotation on turbulence factor for two hole sizes and constant 50 per cent open area. The effects of all three variables are very marked and they also exhibit some



B indicates rolls moving away from slice at common nip

F indicates rolls moving towards slice

Fig. 7—Effect of slice variables on turbulence factor of jet

interactions. The safe level of the turbulence factor was defined as the value for the factor measured with the $1\frac{1}{8}$ in hole size rolls and at the same jet speed as had begun to show streaks in the paper on the commercial machine. Although somewhat arbitrary, this has in fact proved successful in a subsequent practical application of the results. Similar experiments with $\frac{7}{8}$ in holes at the same open area suggest that, with other things equal, the turbulence factor is proportional to the area of the holes—that is (diameter)^2.

Turbulence measurements were made also with rod rolls at the slice and with no rolls at all. The rod rolls gave a turbulence factor value approximately three times the safe figure, with no rolls we obtained a still higher value. The streaks from both these arrangements were more random, large scale and intermittent than with the holey rolls. Large vortices forming along the slice pond plate passed freely out of the slice. Thus, in spite of their many deficiencies, holey rolls do limit the scale, control the intensity and produce a more uniformly turbulent flow to the slice than either a rod roll or nothing at all.

The criteria for roll selection presented by this study does not readily permit reduction to a formula and, as we have already seen above, the final selection is a compromise between jet stability and floc formation by the roll. On a multi-purpose machine, a variable speed holey roll drive at the slice position provides the operator with a very valuable control means to adjust for changing long fibre content and treatment.

The flow to the slice creates two conditions considered to promote preferential orientation of the fibres in the machine-direction—namely, a shear condition across the flow and an acceleration along the flow. The former effect will predominate close to the walls and the second in the body of the jet. Several studies of the orientation of fibres in the finished sheet have been reported and the effects of shake and of jet/wire differential determined. Little is documented of the effect of slice design and this is probably due to the inability of the operator to change it readily on a production machine, also to the difficulty of discriminating between slice design and wire drag effects upon the orientation of the finished sheet. The classical paper of Bryant and Moss[8] was restricted by the techniques then available to low slice velocities and dilute suspensions. Their evidence of strong orientation in the jet has frequently been assumed true under more usual papermaking conditions without any proof. The effect of slice design on fibre orientation at speeds up to 1 400 ft/min and consistencies up to the range of normal head box consistencies has been studied by Wrist and Long, using a high speed flash technique described by Scott.[9]

Fig. 8*a* shows the experimental arrangement and Fig. 8*b* a typical photomicrograph of the fibre arrangement in the jet immediately after the slice for a jet speed of 1 400 ft/min and fibre consistency of 0.06 per cent. Useful results were obtained at consistencies up to 0.5 per cent (Fig. 9).

Three slice types—a 13° nozzle a 30° nozzle and a 90° slice—were studied at different consistencies for two fibre types, one a long-fibred kraft, the other chopped rayon. A very shallow depth of field allowed the orientation at different planes in the jet to be studied separately. A difference was noted between the orientation close to the boundaries and in the body of the jet. Since the body of the jet comprised the major portion of the jet, most of the study was devoted to measurements close to the middle plane. Several shots were taken for each condition and enlarged prints (magnification $\times$ 6) were used for measurements of fibre orientation. Fibre flocculation was assessed visually from contact prints at 1:1 magnification or by using a modified phototube head in conjunction with the QNS-Mead formation tester[10] scanning the jet at a fixed position.

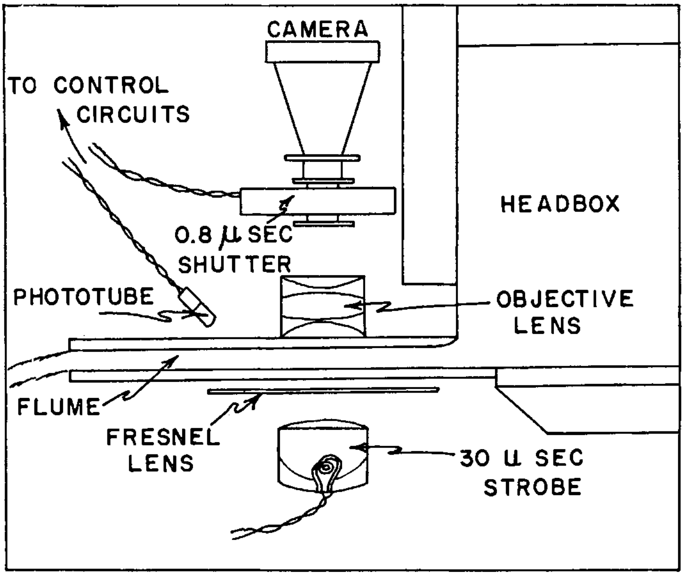


Fig. 8 (*a*)—Photographic arrangement

The mean orientation of a complete fibre is difficult to measure in consistencies above 0.06 per cent. The orientation measurements were therefore made as follows: a transparent mask with a series of fine concentric circles, spaced at a distance equivalent to 5 mm (that is, 3 cm on a $\times$ 6 print) was placed over the print. Since this distance exceeds the fibre length, no fibres will be intersected by more than one circle. Every distinct fibre crossing a circle is included in the sample and the orientation of a 2 mm segment of the fibre at the point it crosses the circle is defined as the statistic. The distribution of angles was obtained for intervals of 5°, centred about each integral 5° increment, that is $0 \pm 2\frac{1}{2}°$ to the flow direction $(5 \pm 2\frac{1}{2}°)$, etc.

The percentage fibre orientation (F.O.) is defined as $(45 - \bar{a})/45 \times 100$ (where $\bar{a}$ = mean angle) and lies between 0 (for fully random) and 100 per cent (for

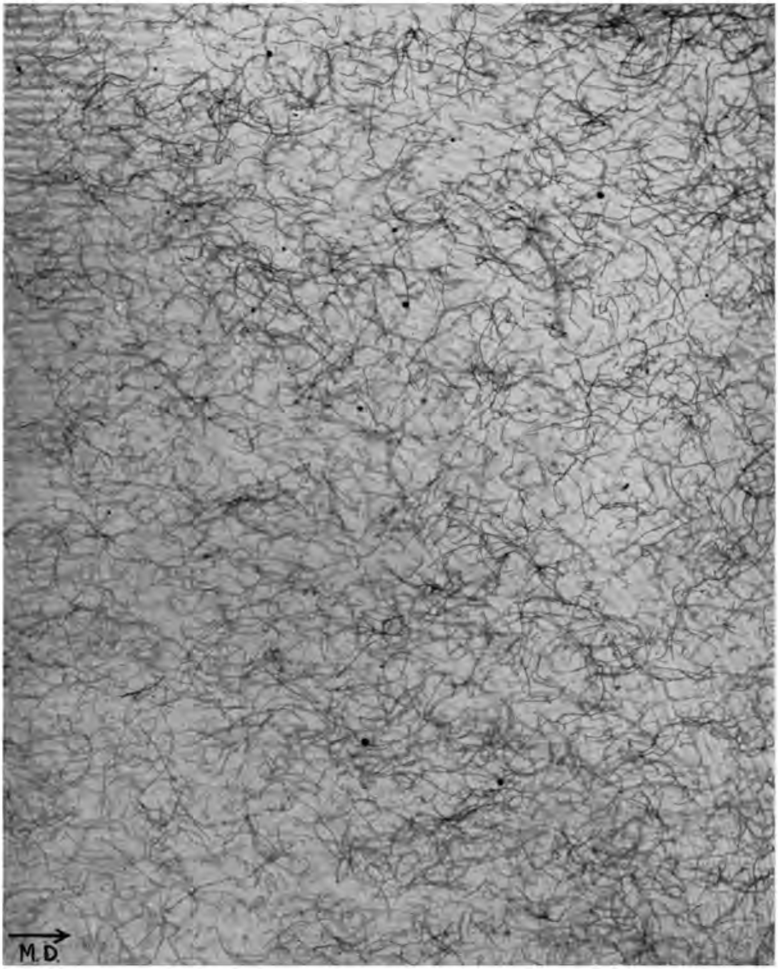


Fig. 8 (*b*)—Photomicrograph of fibres in jet travelling 1 400 ft/min: 0.06 per cent consistency

fully oriented distributions). Although the sampling from individual prints occasionally indicated assymetry about the flow direction, this was not a consistent result and therefore positive and negative angle values were averaged together. Fig. 10*a* shows a typical orientation distribution. It was concluded from this work that the orientation produced at the slice is very

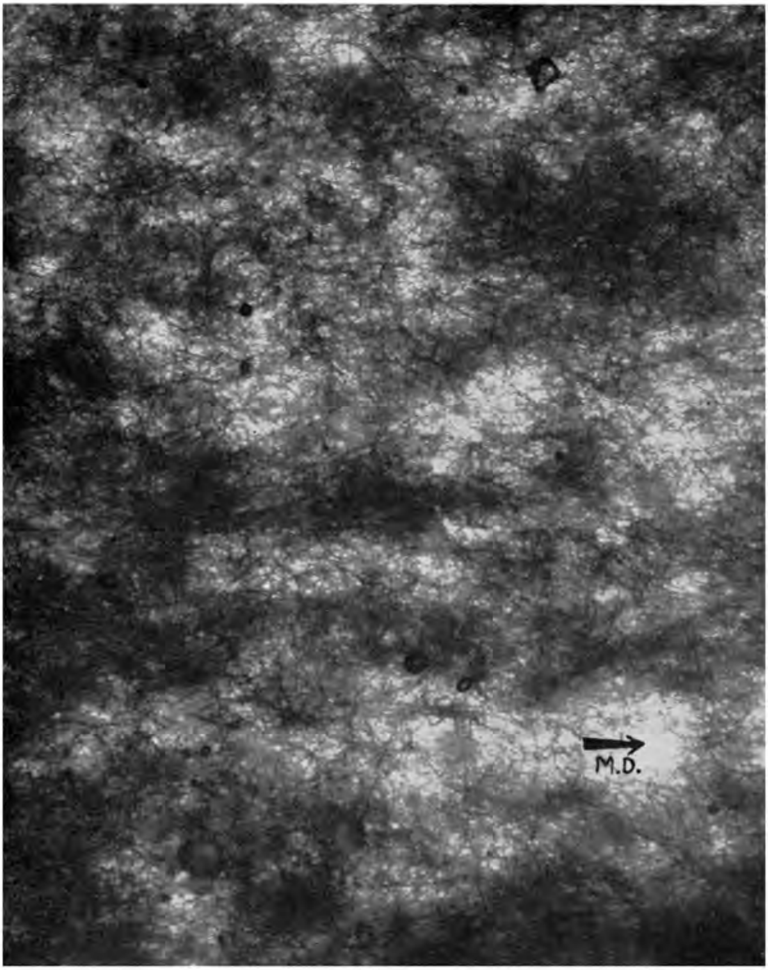


Fig. 9—Photomicrograph jet, 1 400 ft/min: 0.50 per cent consistency

consistency sensitive and that it is a function of the fibre network strength. The slice design and machine speed are important, but of less effect. Fig. 10*b* shows the effects of fibre type, head box consistency and slice nozzle angle on percentage F.O. Results for different speeds form very close families of curves. Interactions between the factors are obvious and are not yet fully understood, although the formation of a dynamic fibre network in suspensions above around 0.15 per cent, a network strength that increases with consistency and a time-dependent reaction of the network to shear and acceleration that may vary with fibre type are indicated.

The flocculation data showed similar dependencies. Fig. 11 shows the variation of the relative floc intensity with floc size (for definitions[10]). Doubling the speed produced only a slight reduction in the number of the

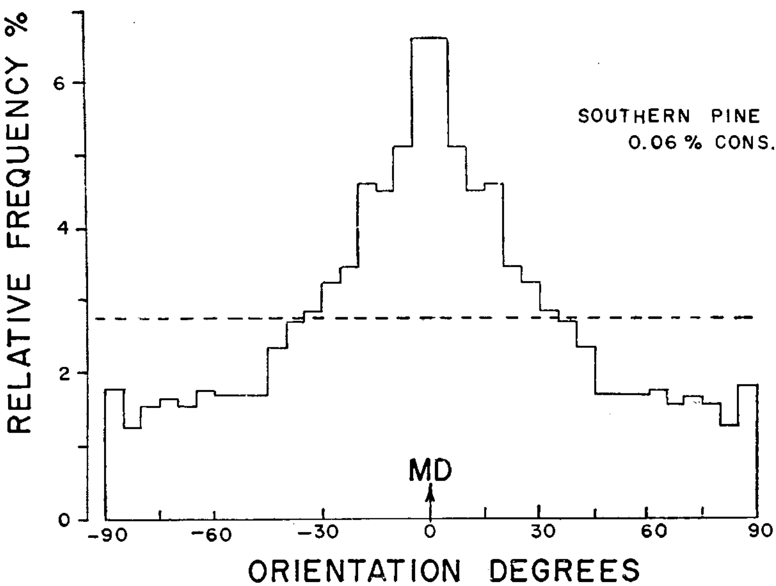


Fig. 10 (*a*)—Typical orientation distribution

largest flocs. Consistency plays the dominant role in determining floc intensity. The floc size noted as *minimum dominant floc size* on the curves appears a characteristic property of a given stock. No matter how well dispersed the stock might be, the peak of the curve was never moved to a floc size below this value. Changing consistency or intensity of turbulence changes the intensity of flocculation, but the scale seems always to be determined by the length of the fibres. In the case of heterogeneous mixtures, the scale is apparently determined by the longest fraction. The minimum dominant floc size appears to lie between one and two times the longest fibre length. The flocculation intensity was always less with the smooth rayon fibre (lower network strength) than with the natural fibres with their fibrillated surfaces under equivalent flow and consistency conditions.

Evidence of the very strong dependence of network strength on consistency has been obtained from other studies. Mason[11] has described the

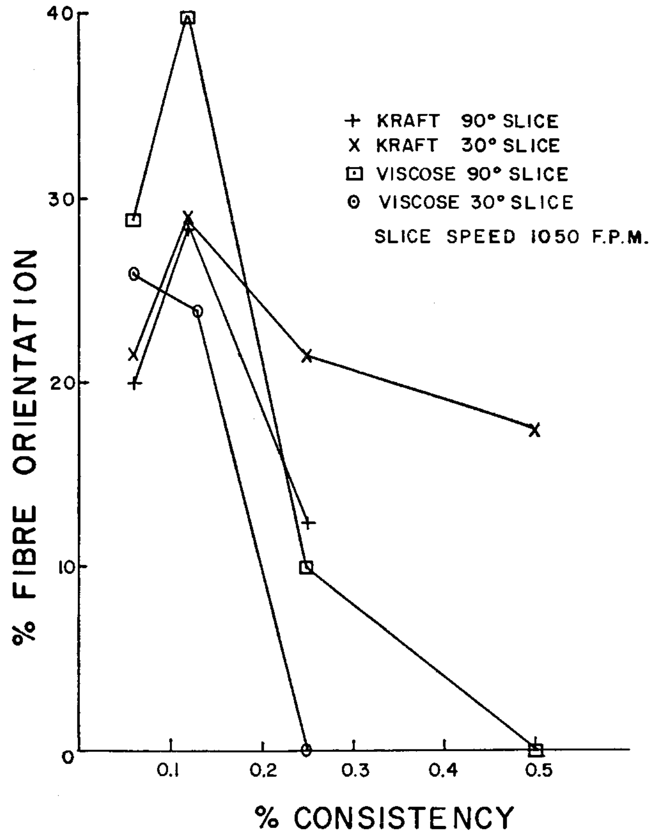


Fig. 10 (*b*)—Orientation factor as function of consistency for various slice arrangements and fibre types

characteristic regimes of the flow behaviour of fibre suspensions in a circular pipe. Transition from a laminar plug flow to a fully turbulent flow of the fibre suspension in the pipe occurs progressively over a fairly wide velocity range. Break-up of the plug starts on the outside and moves inward as the velocity is raised. The shear at the boundary of the plug at the start of the breakdown can be calculated from the transition point in the pressure drop data. This shear may be defined as the yield shear stress of the pulp at that consistency. By varying consistency in the pipe, the relationship of yield shear stress Y_s to consistency C can be determined. Fig. 12 contains typical data computed from the friction factor data of Daily *et al.*[12] and of Wrist and Long.[13] The data may be represented by the equation —

$$Y_s = const. \times C^{n_1} \quad \ldots \ldots \ldots \quad (2)$$

where n_1 is approximately 1.5 in the range of consistency 0.1–1.0 per cent.

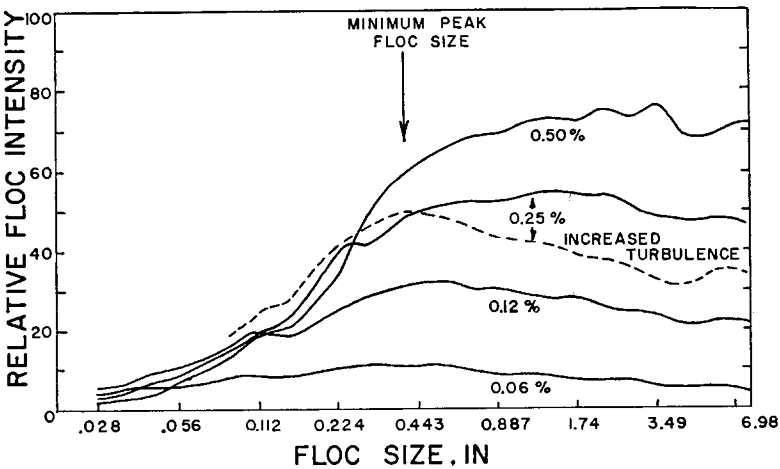


Fig. 11—Relationship of floc intensity to floc size for different consistencies

Combining this result with that of Kurath,[14] that the modulus of shear G is given by* —

$$G = const. \times C^{n_2} \quad \ldots \ldots \ldots \quad (3)$$

where n_2 is approximately 3.0, the yield shear strain Y_e is given by the expression —

$$Y_s = Y_e G \quad \ldots \ldots \ldots \quad (4)$$

so that $Y_e = const. \times C^{n_3}$ . . . . (5)

where n_3 is approximately -1.5.

*The author realises that this is a use of Kurath's data outside the consistency range for which it was derived. It is considered a worthwhile assumption in the present speculative argument.

Parker[15] has noted a similar correlation of yield stress and consistency in the published results of earlier workers and he pointed out that from 1.0 per cent up to 6.0 per cent the value of n_1 approximates 2.5, which gives a value of $n_3 = -0.5$ approx. for this higher consistency range.

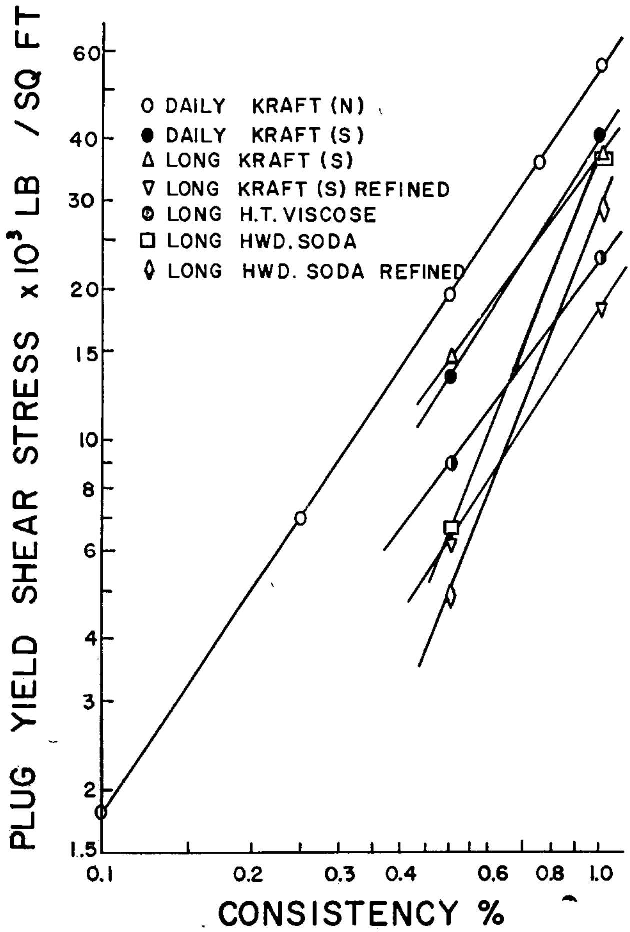


Fig. 12—Fibre network yield shear strength plotted against consistency

Wrist[16] has noted that similar relationships exist between the other elastic quantities and consistency, so that we may expect that the tensional yield strain will be similarly consistency dependent. The negative exponent n_3

means that as consistency is raised the network is less able to elongate on application of a tensile stress and the extension to rupture will decrease. In the slice, the fibre network is subjected to an acceleration. The portion in the slice is moving faster than that a little farther away approaching it. This relative motion produces an extension of the network. If Y_e is exceeded, the network will rupture causing discontinuity in the fibre distribution. This

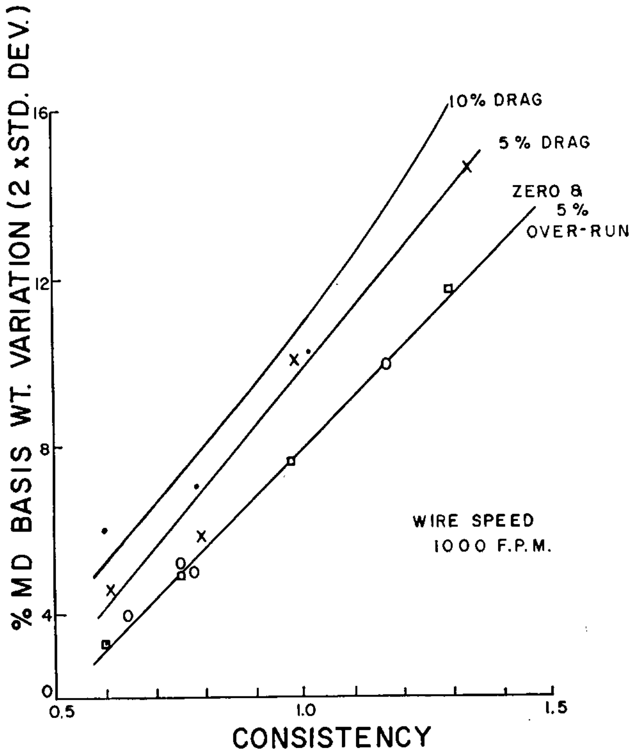


Fig. 13—Relationship of machine-direction weight variations to jet/wire differential and consistency

explains the observations made that intensity and frequency of the gross flocs in the slice flow increased with consistency and that they were less severe in the more gradual acceleration of the 30° nozzle than in the abrupt acceleration of the 90° slice.

Confirmation of these observations have been obtained from an entirely different type of experiment. Wrist and Fisher, studying factors influencing the variations of basis weight in the machine-direction, found the magnitude of the variations to be sensitive to head box consistency, also to the differential speed between the jet and the wire. A velocity differential is equivalent to the continuation of the acceleration of the network beyond the slice.

The results will therefore be similar. Fig. 13 shows the relationships found for a constant wire speed. The weight variations that occurred were not periodic (Fig. 14)—unlike those attributable to pressure pulses from screens, etc.—and the distance between troughs varied randomly with spacings up to 20 in. At low consistencies, the fibre network in a jet, which

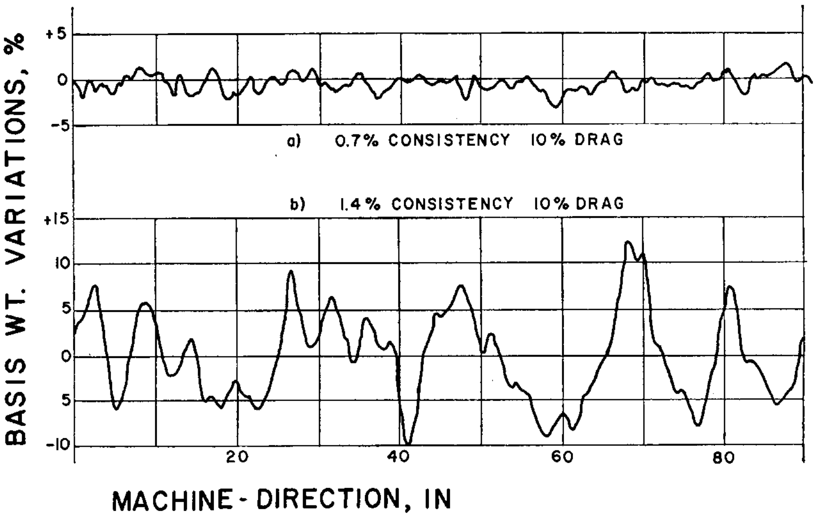


Fig. 14—Machine-direction basis weight variations for —

(*a*) 0.7 per cent consistency: 10 per cent drag
(*b*) 1.4 per cent consistency: 10 per cent drag

has a velocity differential with respect to the wire, is able to 'stretch' on the wire without rupture. As the consistency is raised, the strength of the network of the fibres in the jet increases, but the network's ability to 'stretch' decreases, so that it fractures across the machine at a weak point. The rupture is partially repaired by the turbulent action of the table rolls, but this reblending becomes less effective at higher consistencies and the resulting mass variation is frequently very visible in the form of irregular bands moving along with the wire. At 1.4 per cent consistency, acceptable weight variations could not be obtained with any velocity differential and this conclusion has been borne out in commercial experience.

Turbulence suppression and decay

An important consequence of fibre entanglement and network building in pulp suspensions is the effect it has on turbulence within the flow. In the laminar plug regime (descriptive details[11]), the fibres almost completely eliminate fluid shear within the plug, the fluid shear being confined to the clear water annulus surrounding the plug, while shear forces are sustained within the plug by the fibre network itself. As the plug is gradually broken up in the transition and turbulent flow regimes, the high viscous drag forces acting on the fibres and flocs very rapidly dissipate turbulent energy, particularly that of a scale equal to or smaller than the size of the fibre flocs. Thus, Daily *et al.*,[17] studying the energy spectrum of turbulent flow in fibre suspensions, found that the pulp suspension had about the same energy as for turbulent flow in water of comparable Reynolds number for the lower frequencies (0–30 c/s), but at the higher frequencies the energy level was much lower in the pulp. Parker[15] has studied the decay rate of turbulent energy in pulp suspensions and finds that the smaller the scale (the higher the frequency) the faster the decay rate.

These findings raise a very basic question concerning the head box design. Hitherto, the expression 'making the sheet in the head box' implied the possibility that it should be possible with correct design not only to achieve uniform macro-distribution of the fibres at the slice, but also satisfactory micro-distribution. To overcome the flocculating tendency of fibres in the head box, designs have been developed to create micro-turbulence in the flow of a sufficiently small scale and high intensity as to break up the flocs. We must now conclude that even when such turbulence is introduced in the region of the slice, it will decay so quickly and permit reflocculation that its effectiveness will be completely lost before the sheet is formed on a conventional Fourdrinier machine. The implication, therefore, as stated by Parker, is that 'the need for controlled turbulence to deflocculate the fibres is not in the approach flow (the head box and slice), but rather in the immediate drainage zone where the sheet is being formed. Further, it is probably not necessary to sustain a fine scale dispersion in the approach flow, which would require a large power consumption.' Methods by which the generation of turbulence in the drainage zone can be accomplished are discussed in a later section.

Mass diffusion over the Fourdrinier table

A characteristic of most high-speed machines is the violent agitation of the stock as it passes over the table rolls. A degree of agitation is essential to good formation, especially with long-fibred stocks. Excessive agitation, however, disturbs the basis weight uniformity and the sheet formation and an inability to control it is often the major speed-limiting factor. In addition to the flow instabilities generated over each table roll, the Fourdrinier table as a whole permits a flow instability or flow non-uniformity present at the slice to develop before the sheet is set. A cross-directional velocity component or a variation from the mean machine-directional component at the slice will be transformed into a weight variation over the table. What is the magnitude of these effects?

Mason and co-workers[18] studied the diffusion of mass through various stages of the head box and wire section on two newsprint machines running at 1 600 ft/min. Each machine had a head box with flow-evening vanes, although of different design. They used radioactive tracer fibres added at selected points along the flow to follow the diffusion processes. Within the head box, they found evidence of large-scale turbulent swirls. Tracer additions in the slice zone, however, only showed a lateral spreading of the tagged fibres with an r.m.s. displacement of 0.6 in and no evidence of snaking. This low degree of lateral diffusion is characteristic of slices fitted with flow vanes and, as reported above,[5] the diffusion over the table may be insufficient to blend out the wakes of the vanes, requiring the addition of a cross-machine turbulence rod to obtain an acceptable weight profile.

The degree of diffusion over the table is the combined result of instability and cross-flow components in the slice and of the amplification of these instabilities over the table. It is to be expected, therefore, that it might vary widely from one machine to another. Experiments carried out by Beloit engineers on a high-speed newsprint machine[19] provide evidence of a larger diffusion scale than that found by Mason. In a series of experiments, table rolls were replaced by low vacuum suction boxes. Although utilising low vacuum, the suction area of the boxes is considerably more than that provided by rolls and a general drainage advantage was gained. The objective of the trials was to reduce wire mark and this was in fact obtained. Other

TABLE 1—PERCENTAGE STANDARD DEVIATION COMPONENTS OF BASIS WEIGHT VARIATION

	Total	*Mean profile*	*Residual*
Conventional Fourdrinier with table rolls ..	1.88	1.16	1.49
Fourdrinier with all low vacuum suction boxes	1.19	0.91	0.78
Root square difference between runs.. ..	1.46	0.72	1.27

changes of interest resulted, however: the levelness and stability of the weight profiles improved and the formation of the sheet deteriorated to an unacceptable level. Fig. 15 shows corresponding portions of 'composite' basis weight profiles taken across the machine from successive turns of the reel for the two machine arrangements. The improvement in levelness and stability of the profiles made with the boxes is evident. An analysis of variance[20] for the

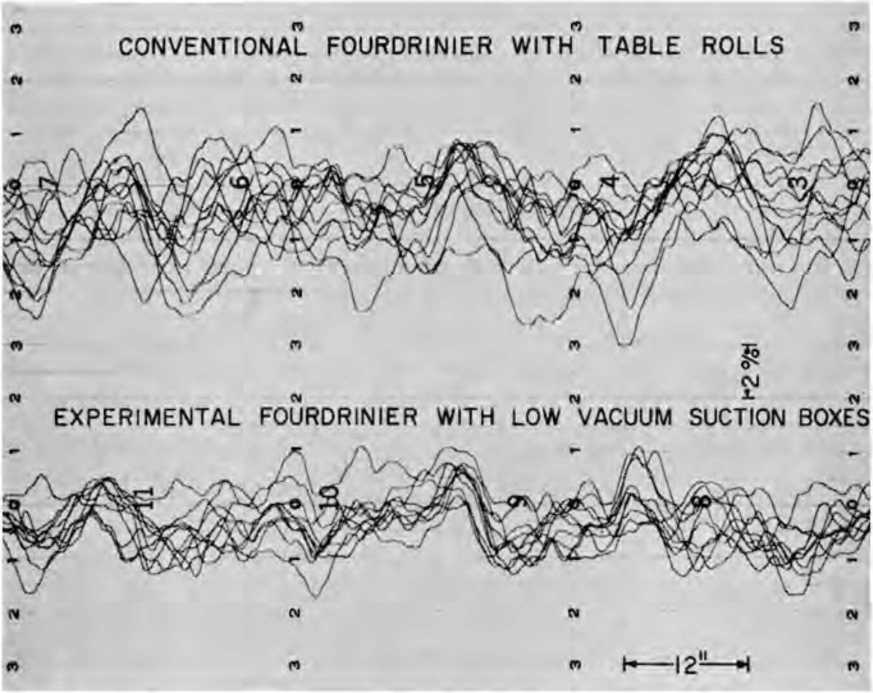


Fig. 15—Composite weight profiles (*a*) with table roll drainage, (*b*) with flat box drainage

two cases shows that the flash variations were reduced by 73 per cent on eliminating the agitation of the rolls and reducing the distance required for setting the sheet.

Some diffusion still occurs over the boxes, but, since the sheet is set in a shorter time and with very little agitation compared with that formed over the rolls, it is justifiable to use the root square difference of the standard deviations between the runs as a measure of mass diffusion occurring over the table roll section of a high speed Fourdrinier. It will be noted in this instance that the table rolls contributed more to the total variation than all the other causes combined, that some of this was due to a worsening of the mean profile, but mostly from an increase in the magnitude of the random variations. From these and similar experiments, we must conclude that the macro-movement of stock over the wire is detrimental to sheet quality.

The micro-diffusion that also occurs, however, is beneficial in improving formation. This is seen in the look through photographs and the formation diagrams[10] of the samples taken during the experiment. The suction box

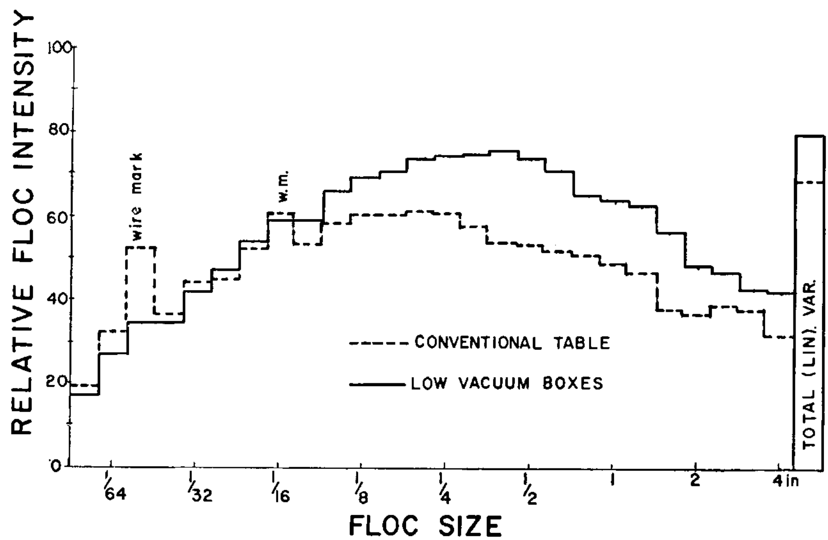


Fig. 16—Formation graphs with table roll drainage and with flat box drainage

sheet has a higher total ('Lin') variation level and its predominant floc size is roughly double that of the 'roll' sample (Fig. 16 and 17*a*, *b*).

Macro-diffusion is caused by cross-flows present in the slice, also by local fluctuations in the mean velocity of discharge. Such cross-flow may be the result of turbulence in the jet, but is caused mostly by the redistribution that arises when the outflow from a point of the slice does not equal the flow approaching directly to that point. The difference may be an excess or deficiency and, since the redistribution will occur over a large sector of the slice, the operator attempting to make adjustments to his slice invariably must work the slice over a much wider area than that of the streak he is attempting to correct. The local fluctuations in velocity from the mean may be in phase across the whole machine if caused by pressure pulses or vary from point to point when caused by non-steady flows in the head box. Basis weight analysis is an elegant tool to study both types and provides a convenient way of characterising head box and stock supply systems. Although the results are of interest in this paper, a study of their causes is outside its scope and the reader is referred to the literature.[2,20–22] Waves from maladjusted deckle boards or straps are other sources of macro-diffusion.

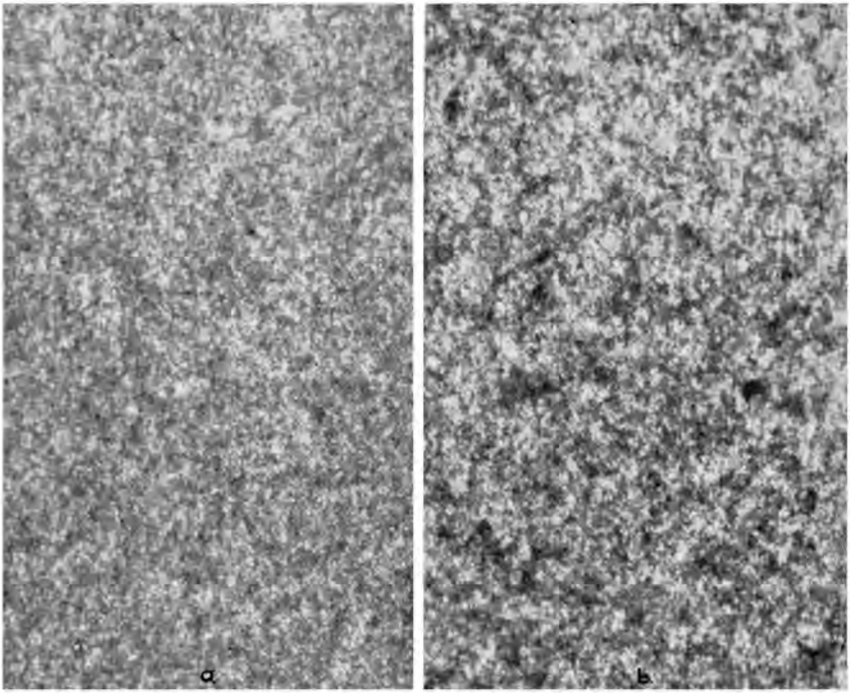


Fig. 17—Look-through photographs (*a*) with table roll drainage, (*b*) with flat box drainage

Micro-diffusion results from one or more causes: jet to wire differential, wire shake, stock jump and small-scale turbulence in the slice flow. All rely on the production of relative motion between the undrained stock and the wire initially and later the fibres that are deposited on the wire as the drainage proceeds. This relative motion produces a combing effect on the depositing fibres, a shearing action on fibre flocs in the slurry that helps to deflocculate them and a transport mechanism by which fibres over a region with more deposited fibres than average (consequently, higher drainage resistance) are moved to nearby areas deficient in fibres. The mechanisms that cause micro-diffusion are considered in the following sections, together with its results.

Free surface instability

IN the last section, the generation of unstable flow conditions in the stock as it passes from the slice over the table roll section was noted. It was suggested that some flow instability is desirable to improve formation on machines without shake, but that excessive instability may destroy the sheet. Since high-speed machines rely almost entirely on this unstable flow to form the sheet, several people have been working to understand the basic mechanisms involved.[23–27] The analysis is complex and has not yet been fully understood. Since the whole phenomenon occurs in a few milliseconds, observations have been carried out primarily with the aid of high-speed ciné and flash photography. Many examples of these are found in the literature cited. The zones of particular interest are the landing area of the jet on the wire, the areas over and immediately following each table roll and the areas over drainage foils (if in use). The feature common to all these is that in them the stock changes its direction of travel. The jet makes a slight angle of impingement on the wire. At the table roll, the stock changes direction two or three times and, at the foil, twice. These changes are shown diagrammatically in Fig. 18. The cause for the deflections at the roll and foil is the hydrodynamic suction created in the outgoing divergent nip. This suction has been studied both theoretically[28] and experimentally[23] and, in spite of the simplifications used in the theory, reasonably good agreement exists between the two. Typical suction profiles for a roll and a foil are illustrated in Fig. 19*a*, *b*. The important features to note are (*1*) the peak suction for the roll is equal to $1/2\rho U^2$, where ρ = density and U = wire speed, (*2*) that the peak suction of the foil is very much less than that of the roll and not so simply related to U and (*3*) the duration of the roll-created suction is relatively short, whilst that of the foil may, through proper choice of angle, be extended over the full length of the foil. Bergstrom[29] has described how the path of the flexible wire deflects over the rolls and his theoretical predictions agreed closely with the experimental data of Burkhard and Wrist.[23] He shows that over the roll the wire conforms for a short distance to the roll surface, that it then inflects and, under the action of the tension in the wire T and the suction in the nip, curves back with a maximum radius of curvature equal to $\rho U^2/2T$. At 2 000 ft/min, this means that the stock is subjected firstly to a constant downward acceleration of $U^2/R \approx 60$ g (where R is the radius of the roll) for a duration proportional to U^2/T (in a typical case about $1\frac{1}{2}$ millisec), followed by an upward impulse during the course of which the acceleration reaches a maximum of approximately $0.78\ \rho U^4/T \approx 130$ g. The reaction of a layer of stock to a steady centrifugal acceleration (which occurs when the stock has a free convex surface) is very different from its reaction to an impulsive centripetal acceleration (with

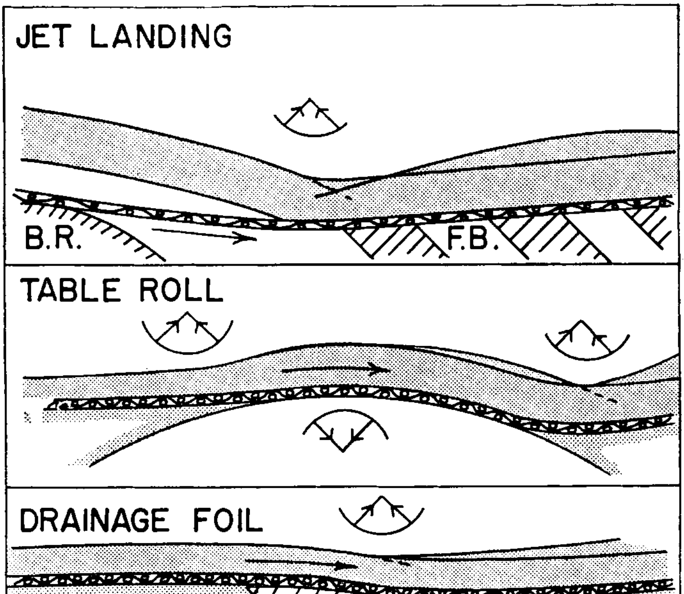


Fig. 18—Diagram of changes of direction taken by Fourdrinier wire over the table

a free concave surface). Over the former, any disturbance of the surface is amplified unchanged; in the latter case, the disturbance is rapidly inverted by the impulse and the inverted disturbance pattern then continues to grow for quite a period afterwards. If the amplification is allowed to continue long enough in the former case or the impulse is large enough in the latter, portions of the surface will eventually break away and create 'spouting' and 'stock jump' or 'kick up'. The disturbances from the slice, as we have seen, are usually in the form of streaks. Over the foils or the table rolls, these streaks may still persist, but there may also be bubble pits and other two-dimensional disturbances. If no pronounced disturbance exists already, the first roll or foil will create a regularly spaced one, which will then be perpetuated by the following rolls. This is shown in the four photographs of Fig. 20, in which examples of both types of acceleration are found.

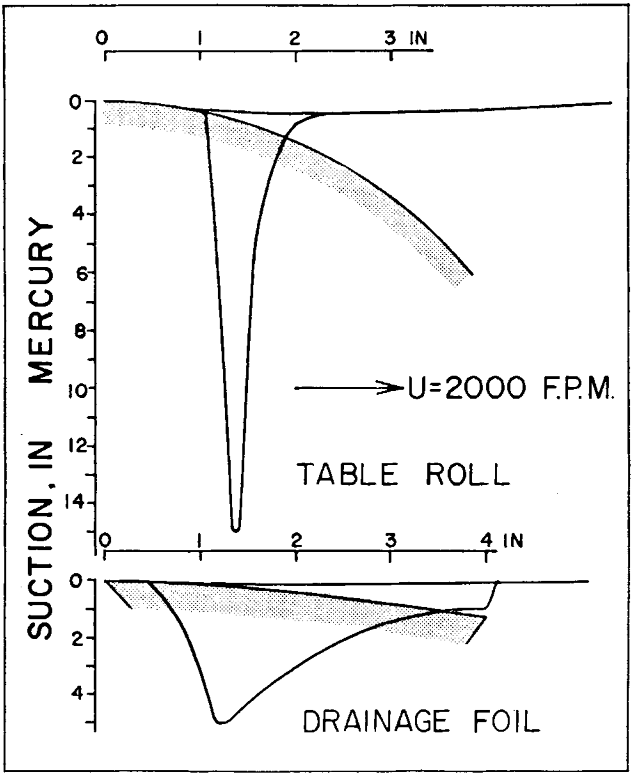
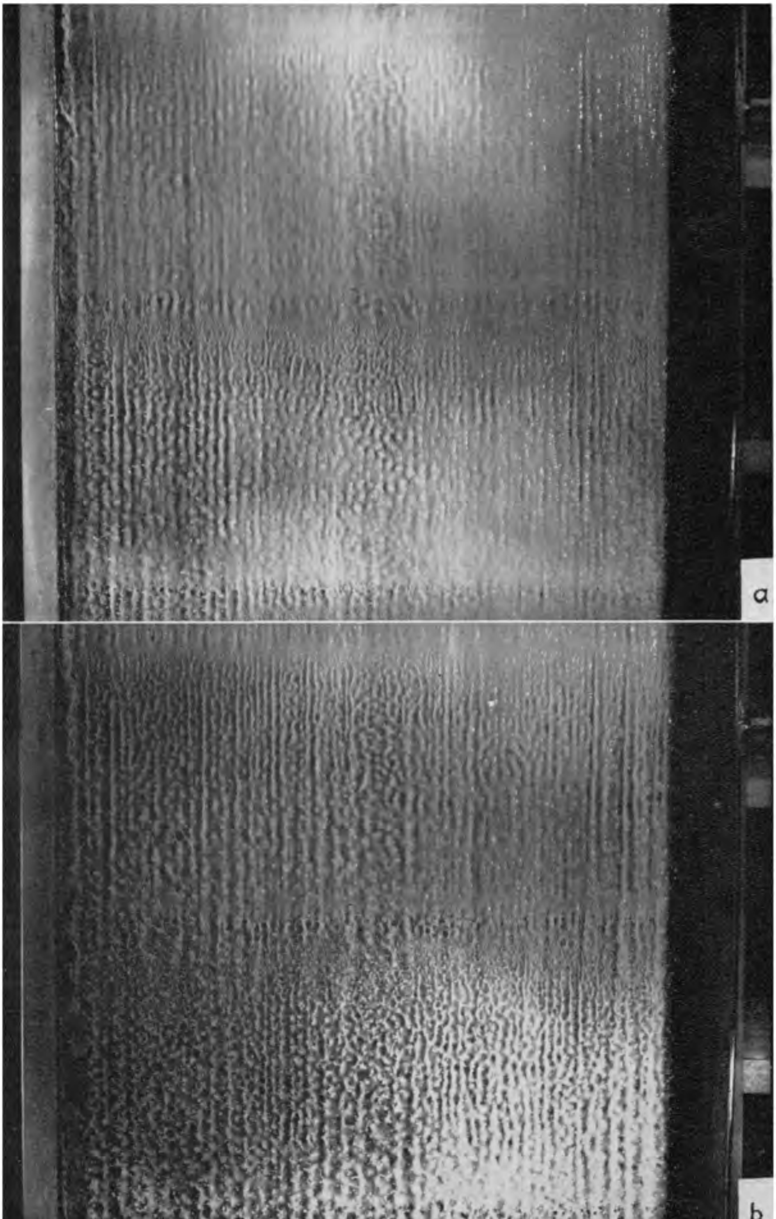


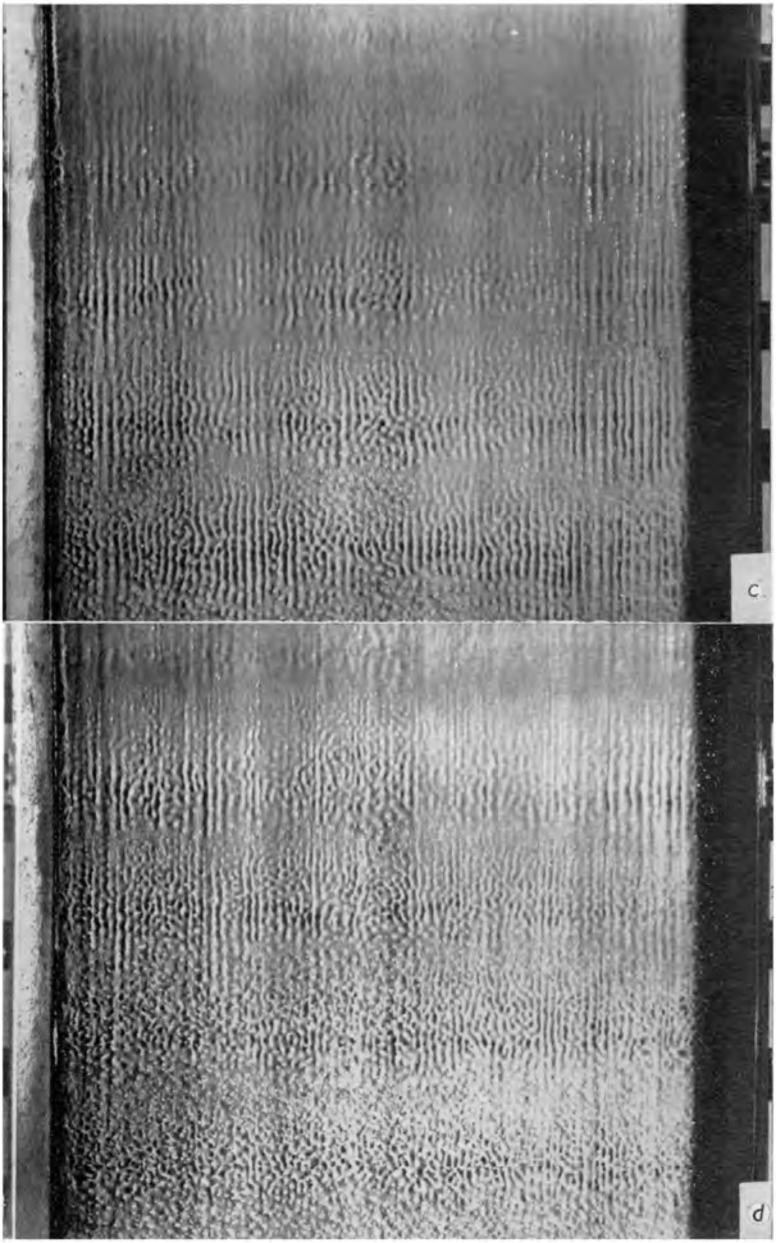
Fig. 19—Suction profiles for (*a*) roll, (*b*) foil

Note particularly the amplification without reversal over the roll wrap region, followed by an inversion and a second phase of amplification starting over the suction zone, which reaches its maximum growth well past the termination of the suction zone. The spouts from a roll invariably develop following the second or centripetal phase, whereas the spouting from the foils develops during the centrifugal phase.



(*a*) over second table roll, 1 500 ft/min
(*b*) over second table roll, 1 800 ft/min

Fig. 20—Photographs of stock disturbances over drainage devices



(*c*) over first–fifth foils, 1 500 ft/min
(*d*) over first–fifth foils, 1 800 ft/min

Fig. 20—Photographs of stock disturbances over drainage devices

The mechanism of instability growth during the centrifugal phase is generally agreed to be equivalent to that proposed by Taylor[30] to describe the behaviour of the waves on the interface of two fluids, accelerated at rightangles to the interface. The most complete and complex analysis is that of Yih,[26] who took surface tension, viscosity, roll curvature and roll speed into account. The details of the theory need not concern us here, except to note that, in common with the simpler theories, it predicts a minimum spacing of the disturbances below which no amplification occurs; a disturbance with critical spacing (on a conventional machine, this is in the order of 0.5–1 in), which will grow most rapidly and therefore which, in the absence of an initially prominent disturbance, will be the one that will be self-generated; and a growth rate that is exponential and a function of the roll diameter, machine speed and surface tension. The photographs in all cases show spacings close to the critical and it will be noted that the spacings in both roll and foils decrease inversely with speed. The same theory may be used to explain the formation of drainage curtains in the water draining away from the roll over its surface.

The theory predicts only the initial growth rate of the waves and evidence suggests the rate of growth changes once the wave has grown in amplitude beyond one seventh of its wavelength. Beyond this point, the crests of the disturbances appear to move independently of the rest, according to their acquired velocity. This second phase is rarely reached over the roll, but is common over the extended suction zone of the foil.

The mechanism of growth in a centripetal phase has not yet been satisfactorily described theoretically. Lamb[31] has studied this phase experimentally in isolation, using an artificially produced surface disturbance. He found that the wave pattern inverted, then the new crests grew at a fairly uniform rate, which increased as a power of the speed. Yih[25–27] and Mardon[24,32] have studied experimentally the centripetal phase after a table roll. Yih attempted to correlate the total growth of the wave by dimensionless group analysis and Mardon measured the trajectory of the crests alone. Mardon makes no reference to the change from centrifugal to centripetal acceleration over a roll and interprets the growth in the latter phase in terms of the theory of the first. He finds that the growth is initially very rapid, the crest growing according to an exponential law. This is followed by a slower growth rate, then a decay period.

The energy for all these disturbances is supplied ultimately by the couch drive. It is transmitted from the couch to the various parts of the table by the wire and as a result the wire tension changes at every point of energy output. Total power needs for a Fourdrinier have been reported in the literature, especially in connection with studies of vacuum boxes. The power consumption over an individual table roll or foil is a more difficult thing to determine. An attempt to do this has been made by Schiel and Wrist.

The table roll of an experimental machine was mounted in a cradle as shown in Fig. 21. The roll bearing is carried on a flexible strip clamped just above wire level. Deflection of the strip is measured by strain gauges attached on either side. The change in the wire tension as it passes over the table roll creates a torque that in turn deflects the strip. The system is calibrated statically. The effect of the bearing friction on the strain gauge

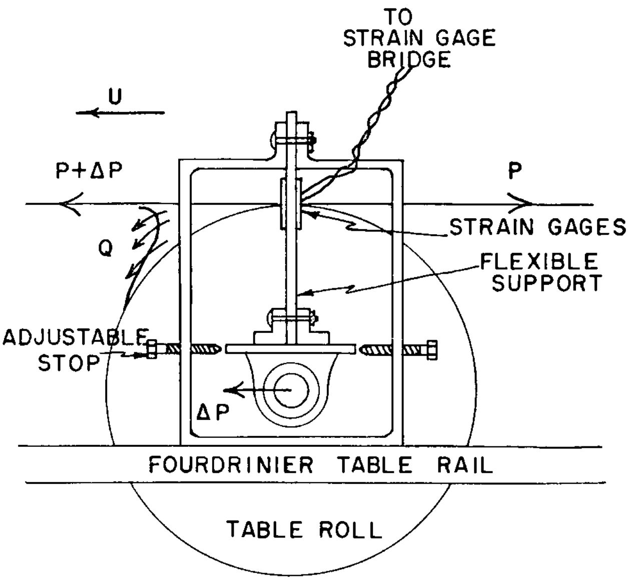


Fig. 21—Apparatus used to measure table roll drag forces

reading can be eliminated by centring the gauges about the wire level. The power transferred from the wire to the roll, thence to the stock, was determined over a wide speed range and at different locations along the table. A typical power curve is shown in Fig. 22*b* for three table roll positions with a groundwood/kraft furnish. The measurements were quite repeatable, as was the drainage at the roll, which was also measured. The power HP_n and drainage Q_n curves at a given roll (n th) were satisfactorily represented by the equations —

$$HP_n = aU^{2\cdot 8} \qquad (6)$$

$$Q_n = bU^{1\cdot 2} \qquad (7)$$

where a and b are constants.

The possible uses of this power are to provide the power for drainage, to provide the power to flex the wire and to provide the power to generate

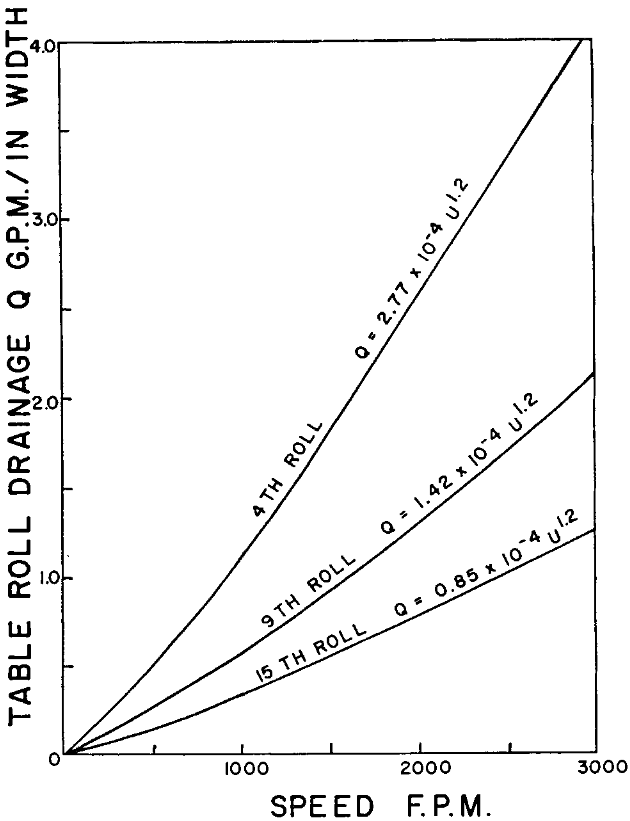


Fig. 22(a)—Drainage on table roll as function of speed

the instabilities in the stock over the roll. The curve shown in the figure was obtained with flat top deflectors supporting the wire between the rolls. When these were removed, the drainage at the ninth roll increased by 13 per cent, the power consumed by the roll rose by 45 per cent and the agitation on the wire also increased. It is reasonable to conclude, therefore, that most of the power consumption at a table roll goes into agitation of the stock. On a production machine at high speed, agitation may consume upward of 100 h p, which far exceeds the rate of power supplied to the stock by a shake motor on slower machines.

The papermaker has a certain degree of control over these disturbances,

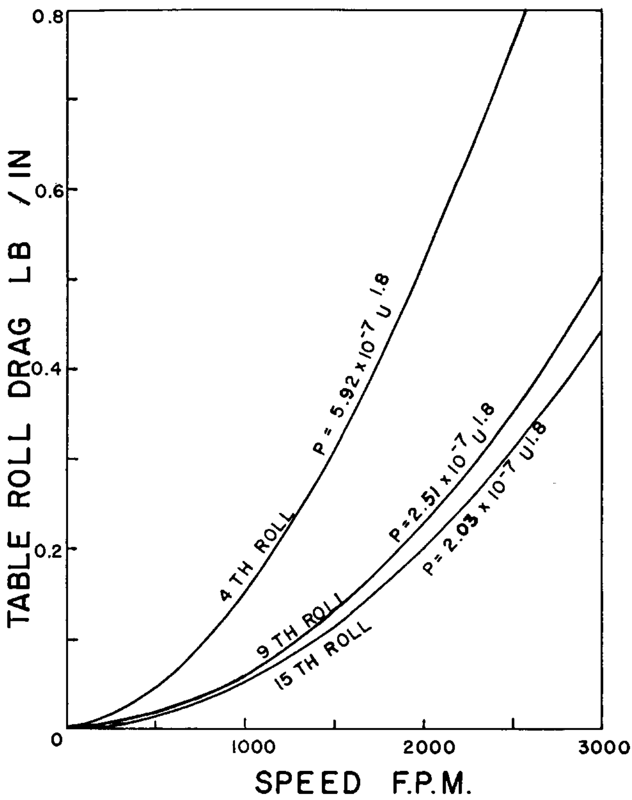


Fig. 22 (*b*)—Power consumption by table roll as function of speed

although the fact that they increase with the 2.8th power of the speed means that his controls very quickly lose their effectiveness as the speed increases. Wire tension should be run as high as possible to minimise the disturbances. Unfortunately, the worst disturbances occur at the first few table rolls, where the tension is at a minimum and, at high speeds, the tension in the return stretch cannot be raised very high without the possibility of a wire tensile failure at the couch. Wire-supporting deflectors may add more themselves to the power load than they relieve at the table rolls. Grooved table rolls and foils can be used to reduce the disturbances and gradually raise the consistency on the wire to a point at which the disturbances are less violent. Grooved rolls must be used with caution, however, since too many may reduce the disturbances and so remove the action of a controlled agitation until the sheet is too immobile to benefit from it, much as the low vacuum suction boxes did in the trial referred to above. Another area of control possible is in the adjustment of the slice discharge angle and of the forming board design and adjustment. The impingement angle of the jet should be small and the wire supported at the point of impact. Wrist and Burkhard[23] further showed how it was possible to combine foils with the forming board in such a way as to minimise the disturbances created at impact. Reducing the roll diameter *per se* decreases agitation; on going to higher speeds, it is usually necessary to increase the roll diameter to obtain mechanical stability, so that all a papermaker can do is avoid using rolls larger than necessary.

In addition to the damage to the forming sheet caused by excessive agitation, there are other deleterious effects. Fine and filler material is less easily retained in the sheet. Wrist and Burkhard[23] found that the whitewater consistency rose linearly with speed. Air bubbles may be generated or trapped in the sheet and appear as pock-marks in the sheet[33] and airborne spray, having lost velocity by air-drag, on landing creates disturbances in the sheet at a stage when it is no longer sufficiently mobile to be smoothed out again.

Formation theory

So far, we have been concerned with the behaviour of the suspension over the wire. The formation of the sheet itself can be considered from the viewpoints of fibre classification by the wire, drainage/suction relationships and fibre dispersion and arrangement.

Very little progress has been made in predicting the retention of the fibres on the wire when drainage occurs. S. T. Han has proposed an empirical relationship based on a series of actual machine measurements. According to Han, the consistency of the filtrate $C_w(t)$ at time t after the start of filtration is given by the equation —

$$C_w(t) = C_o e^{-\beta B(t)} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (8)$$

where C_o = the filtrate consistency at $t = 0$, $B(t)$ is the weight of fibres retained on the wire up to time t and β is a constant.

This relationship is useful for studying the progress of filtration, once C_o and β are known. There is little experience, however, by which C_o and β can be predicted from a knowledge of wire mesh size and fibre length distribution. Han's equation can be expressed in terms of the fibres retained on the wire as follows—

$$C_e(t) = C_s - C_w(t) = C_s - C_o e^{-\beta B(t)} \quad . \quad . \quad . \quad . \quad (9)$$

where $C_e(t)$ is the effective or retained consistency at time t and C_s is the initial slurry consistency.

Estridge[34] has examined theoretically the possibility of predicting the initial rate of retention for idealised fibres and grids. The initial rate of retention r_i is given by —

$$r_i = \frac{C_e(o)}{C_s} = \frac{C_s - C_o}{C_s} = 1 - \frac{C_o}{C_s} \quad . \quad . \quad . \quad (10)$$

Estridge considered the cases of parallel grids spaced b units apart, also of square-sided grids of side b. Assuming a constant fibre length L, he obtained the curves for initial retention as a function of b/L shown in Fig. 23. The experimental points from his own work, also some from Andersson and Bartok[35] are in good agreement with his theory. His theory requires some modification in the practical case to take account of heterogeneous fibre lengths, flexible fibres and non-planar grids (woven wires). It is expected, however, that the retention curve will have a similar shape. In this case, the r_i value could be used to predict the C_o term of Han's equation. To extend this approach to subsequent retention, Estridge proposes that the deposited fibres at time t be assumed to act as part of the grid and that a new value of the characteristic dimension b be calculated. The retention at time t would then be assumed to equal the initial retention value for a grid with the recalculated characteristic dimension b'. The course of the filtration could therefore be followed by an integration process.

Estridge proposes that the characteristic dimension b' at time t be given by —

$$\frac{db'}{b'} = -k\, dB(t) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where k = constant,

so that $$\log \frac{b'(t)}{b} = -k\, B(t) \text{ and } \frac{b'(t)}{L} = \frac{be^{-kB(t)}}{L} \quad . \quad . \quad (12)$$

Noting that in the case of the parallel grids the b/L to r_i relationship is essentially linear, we have —

$$r(t') = (r_i)_{b=b'} = 1 - C_w(t)/C_s = 1 - ab'/L \quad . \quad . \quad . \quad (13)$$

$$\frac{C_w(t)}{C_s} = \frac{ab'}{L} = \frac{ab}{L} e^{-kB(t)}$$

$$C_w(t) = \frac{C_s ab}{L} e^{-kB(t)} = C_o e^{-kB(t)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

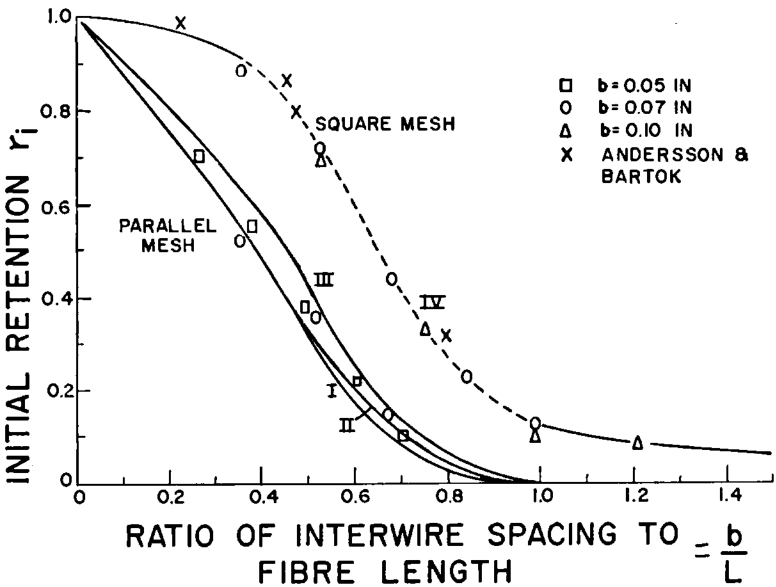


Fig. 23—Initial retention of ideal fibres by parallel and square mesh grids (after Estridge[34])

which is the same form as Han's empirical equation. Although the assumptions are oversimplified, this shows the type of application possible. The statistics of two dimensional random fibre assemblies have been studied by Kallmes and Corte[36] and this type of approach would be useful in a more detailed extension of Esteridge's theory.

Estridge's analysis shows that retention is a function of fibre length. Initially, therefore the longest fibres will be preferentially retained. As these in turn become part of the grid system, the retention of the shorter fibres will be increased. The fact, therefore, that for practical reasons we use relatively coarse Fourdrinier wires (compared with fibre dimensions) of itself introduces a fibre length distribution through the sheet thickness and fine fibres and loading material will be concentrated toward the felt surface. This fact is reflected in the use of extremely fine mesh wires on certain grades of speciality papers for which the furnish contains a large percentage of fine material and when extreme duplexity would be detrimental.

Another factor contributing to the structural duplexity is the backwashing of the sheet by water that had previously drained from the wire

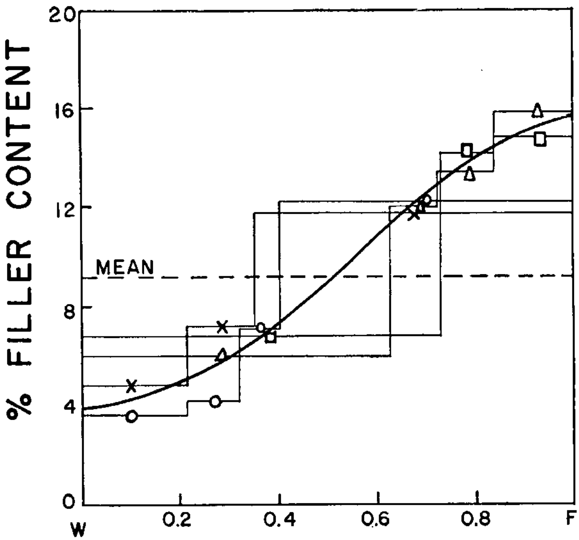


Fig. 24—Distribution of filler through paper sheet

being pumped back in on the ingoing nip of the succeeding table roll. This has been studied in some detail by Underhay.[(37)] By means of successive stripping of the sheet by adhesive tape, it is possible to construct a distribution of loading material through the sheet. A fibre length distribution would also be possible, but very laborious.

Fig. 24 shows both the reproducibility of this method, also the very steep gradient that exists through the sheet. In a series of experiments by Jordansson and Wrist, with different drainage set-ups on the Fourdrinier, it was not found possible to change the distribution to any real extent. Since these changes did involve significant changes in the amount of backwashing that occurred, it might be concluded that the selective retention process of the forming sheet is the more important factor in creating duplexity.

At very high speeds, not only does the non-uniform fibre distribution

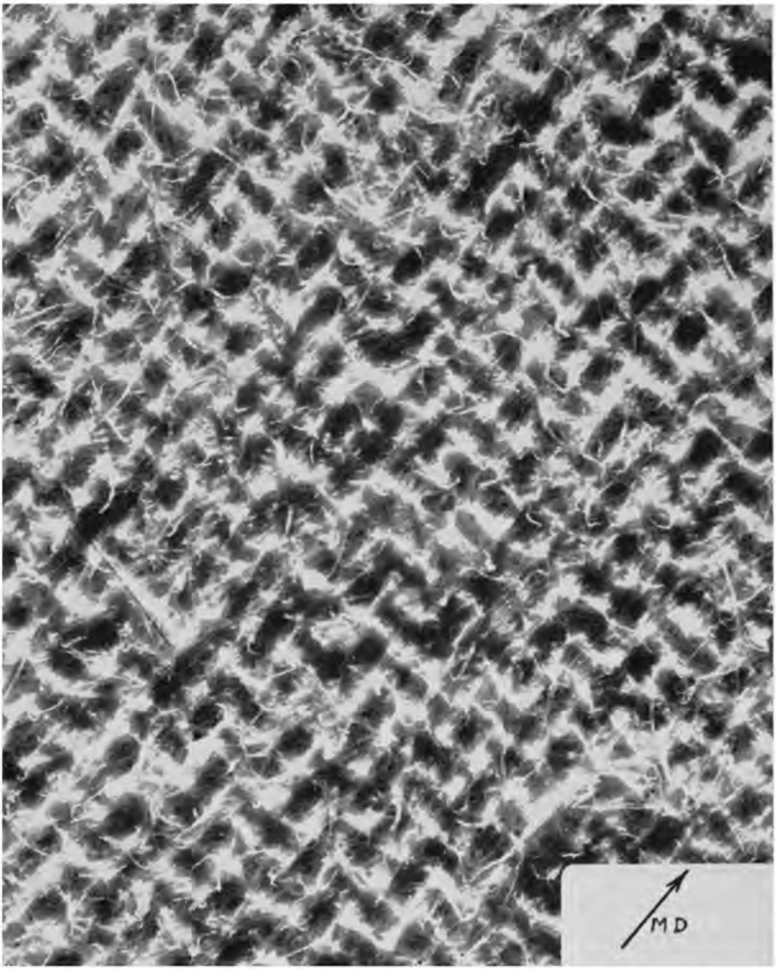


Fig. 25—Photomicrograph of wire side of groundwood/kraft sheet at 1,500 ft/min

create problems, but in addition the very rapid rates of deposition of the first layers of fibres cause some fibres to be drawn into the structure of the wire. When the sheet is a light one, this process leads to very large variation of mass distribution with the pattern of the wire mesh. In addition, many of the fibres on the wire side have a very large z orientation component. This is seen in Fig. 25, which shows the wire side of a sheet taken directly from the wire. Subsequent pressing is unable to overcome the problem completely. Any step that reduces the initial rate of water removal has been found to reduce this effect. In addition, furnish selection plays a very significant role. Groundwood content sheets and other short-fibred sheets are the worst offenders. By selective staining of a groundwood sheet, it was established that the fibres that are drawn into the wire structure, then give rise to the wire mark are predominantly groundwood, not the long-fibred kraft. The chunky groundwood bundles or the short-fibred hardwood fibres are the ones that, because of their shape and size, are able to move more freely through the fibre network structure over the wire.

The study of the drainage/suction relationships as they occur over the Fourdrinier has made a small amount of progress. Taylor's drainage equation[28] —

$$Q_n = 1/2(0.590)\ \rho^2\ RU^3 \left(\frac{k_n{}^2}{\mu}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

where Q_n is the drainage/unit width at the nth roll and k_n = the permeability of the stock over the nth roll, has been the basis of this work.

This equation is based on an experimentally confirmed suction profile prediction and on a statement of Darcy's law. Using this equation, it is possible from drainage measurements on an actual machine to calculate the average drainage resistance $1/\frac{k}{\mu}$ of the stock at each table roll. Wrist,[38] Ingmanson[39] and others have used this approach to establish the variation of drainage resistance along the table. Recognising that the resistance is a result of the already formed mat, both these authors have correlated the resistance with the calculated formed mat weight rather than with the table roll number.

The formed mat weight per unit area at the nth table roll W_n is found from the equation —

$$W_n = \sum_1^n \frac{C_s - C_w(n)}{1 - \dfrac{C_s}{C_m}} \cdot \alpha \cdot \frac{Q}{U} \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where $C_w(n)$ = whitewater consistency at the nth table roll,

C_m = consistency of the mat and is assumed constant along table,

α = conversion factor between units of Q, U and W.

A typical relationship for $1/\frac{k}{\mu}$ against W_n is shown in Fig. 26.

The slope of this curve is defined as the differential specific drainage resistance. The justification for such an approach is based on the belief that it will eventually be possible to predict the differential specific drainage resistance from laboratory testing of the furnish under which conditions table roll number would have no relevance. Tellvik and Brauns,[40] on the other hand, have used a correlation with table roll number and found that the drainage at a given roll is described by the formula —

$$Q_n = \frac{2R}{F^2} \cdot U^{\alpha} \qquad \qquad (17)$$

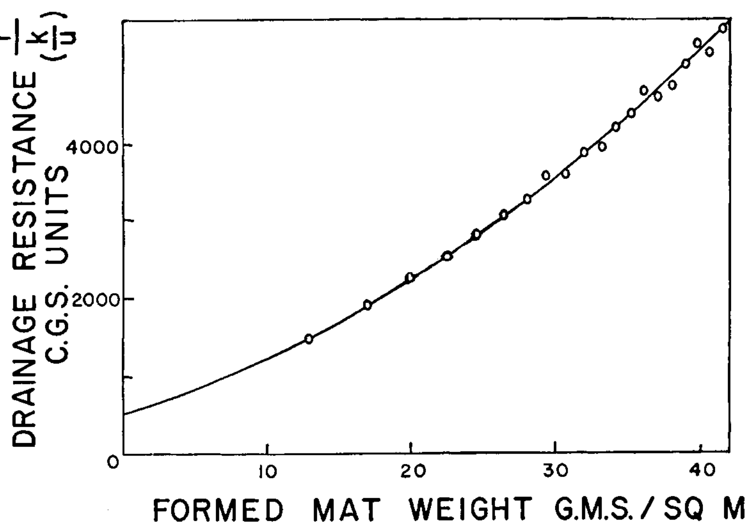


Fig. 26 —Drainage resistance against formed mat weight for typical machine

where F is a filtration factor and $\alpha = 0.3$ for kraft stock and 1.2 for newsprint stock. This correlation is in agreement with that of Schiel and Wrist above. Tellvik and Brauns suggest that, although this approach may be useful under fairly constant machine conditions, it does not offer any way other than actual mill trials to determine α and F and they recognise that these values may change for the same pulp under different operating conditions.

The first step in an attempt to formulate drainage resistance on a papermachine based on laboratory permeability of filtration experiments is the ability to formulate the course of laboratory filtration experiments accurately. Filtration theory for pulp suspension is complicated by the compressibility and high porosities that occur in the forming pulp pad. The approach to permeability of uniformly compressed pads used by Robertson and Mason[41] is restricted to a porosity range of about 0.6–0.8. Within this range, the permeability k of the pulp, defined by the Darcy equation —

$$\frac{Q}{A} = \frac{k}{\mu} \cdot \frac{\Delta P}{L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where Q/A = flow rate across unit area,
μ = viscosity,
$\Delta P/L$ = pressure gradient along flow direction,

may be represented by the relation due to Kozeny and Carman that —

$$k = \frac{\epsilon^3}{\kappa\ S_v^2\ (l{-}\epsilon)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

where κ = Kozeny constant and equal to approximately 5.55 for fibrous mats,
S_v = surface area per unit solid volume,
ϵ = porosity.

For ϵ above 0.8, this relationship breaks down and Ingmanson[42] has shown that from 0.6–1.0 the permeability of uniform synthetic fibres is best correlated to porosity by the empirical relationship —

$$\frac{1}{k} = aS_v^2 \ . \ (l{-}\epsilon)^{3/2} \ . \left[1 + b(l{-}\epsilon)^3\right] . \quad . \quad . \quad . \quad (20)$$

where a, b are constants equal to 3.5 and 57, respectively. A similar correlation was found by Davies[43] for air flow through fibrous filters.

Theoretical support for a relationship of this nature has been provided by Happel,[44] who solved the Navier-Stokes equation for viscous flow through parallel arrays of cylinders. The Davies-Ingmanson relationship is enveloped in the range $0.6 < \epsilon < 1.0$ by Happel's theoretical curves for flow along the cylinder array and flow across the cylinder array. Thus, in extending the use of the Davies-Ingmanson correlation to natural fibres, Ingmanson made the reasonable assumption that the resistance to flow of a natural fibre is equal to that of a cylindrical fibre of equal surface area and length.

Ingmanson has combined this correlation with the differential form of

Darcy's law and the empirical correlation of compressibility of fibrous mats first proposed by Campbell namely —

$$C = mp^n \quad \quad (21)$$

where C = consistency,
p = applied pressure,
m, n = constants

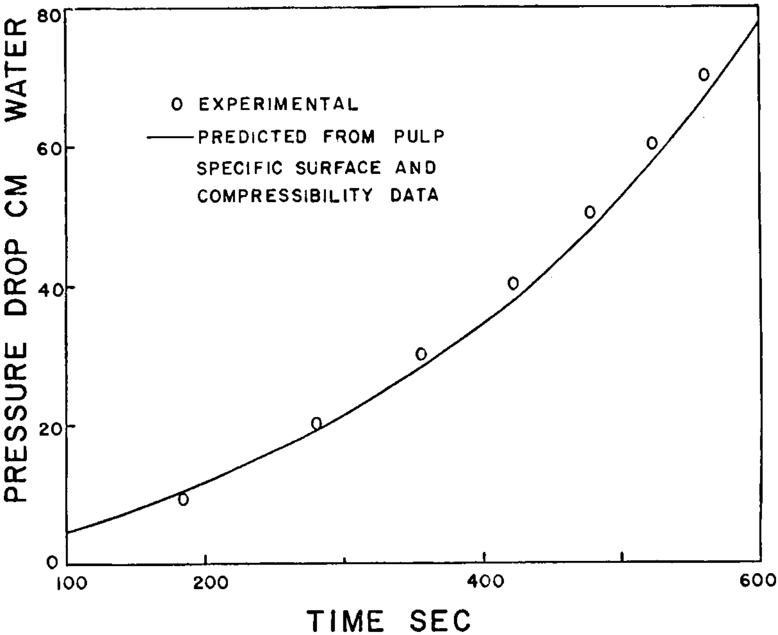


Fig. 27—Comparison of experimental and predicted pressure against time relationship for a constant rate filtration (Meyer[45])

and has used these relationships by graphical techniques to determine the specific surface S_v and the specific volume v of natural fibres, thence to predict the porosity distribution and pressure distributions within a filter mat. The very close agreement between prediction and measurement that he obtained gives confidence to the method.

Meyer[45] has generalised this approach and added continuity considerations, also the variable retention equation of Han discussed above, to those used by Ingmanson. In addition, he has provided numerical methods of solution in place of the graphical ones used by Ingmanson. The result of this work to date is that the course of laboratory filtration experiments may be predicted from a knowledge of specific surface and volume and of the pulp compressibility constants for constant pressure or constant rate and constant or variable retention filtration. Fig. 27 shows the results of such a prediction for a constant rate filtration and indicates agreement within experimental accuracy with an actual experiment.

Before this type of study can be applied completely to the Fourdrinier, it will be necessary to find a way to account for the effect of formation on drainage and to study the effect of a rapid cycling of pressure on the compressibility relationship. Meanwhile, however, the association of the basic pulp parameters indicated by this analysis may provide empirical drainage correlations to be made that can be applied over wider operating conditions than those presently possible with an approach such as that of Tellvik and Brauns.

The most complete study of the way the fibres are laid down in the sheet is that of Finger and Majewski.[46] Other works have studied the orientation of the longer fibres in the sheet, pointing out the differences that may exist between the two sides. The data collected by Finger and Majewski and others using their techniques of sheet delamination indicate that over a Fourdrinier—

1. The sheet is laid down in layers into which it preferentially delaminates.
2. These layers vary in number according to the weight, also to the freeness of the sheet—freer sheets giving fewer plies than slower sheets.
3. The fibres in the individual layers are not always in the plane of the sheet and the sensitivity of the stripping action to direction in the sheet, suggestive of a 'shingling' effect, reflects the relative direction of the stock flow over the forming mat at the time of deposition.
4. The flocculation in individual layers may vary considerably and usually shows a deterioration from wire side to top side.

Finger and Majewski attribute the layered structure to the discrete steps of the drainage process and, in particular, the layers from the wire side up represent the fibres deposited at successive table rolls. The decreasing layer thickness also reflects the decreasing amounts of drainage occurring at each roll. Working with a machine equipped with a variable shake, they demonstrated that the fibres in any layer reflect the relative motion of the free slurry at the instant the layer is deposited. To explain this, they postulated that the fibre becomes vertically oriented over the suction zone by the acceleration produced—likening it to the orientation produced at the slice. One end then becomes anchored and the other is carried over with the flow. In the light of our more recent knowledge of fibre network and orientation effects, this is not now thought to be a correct interpretation. We have seen from the work of Ingmanson and Meyer, however, that the boundary between

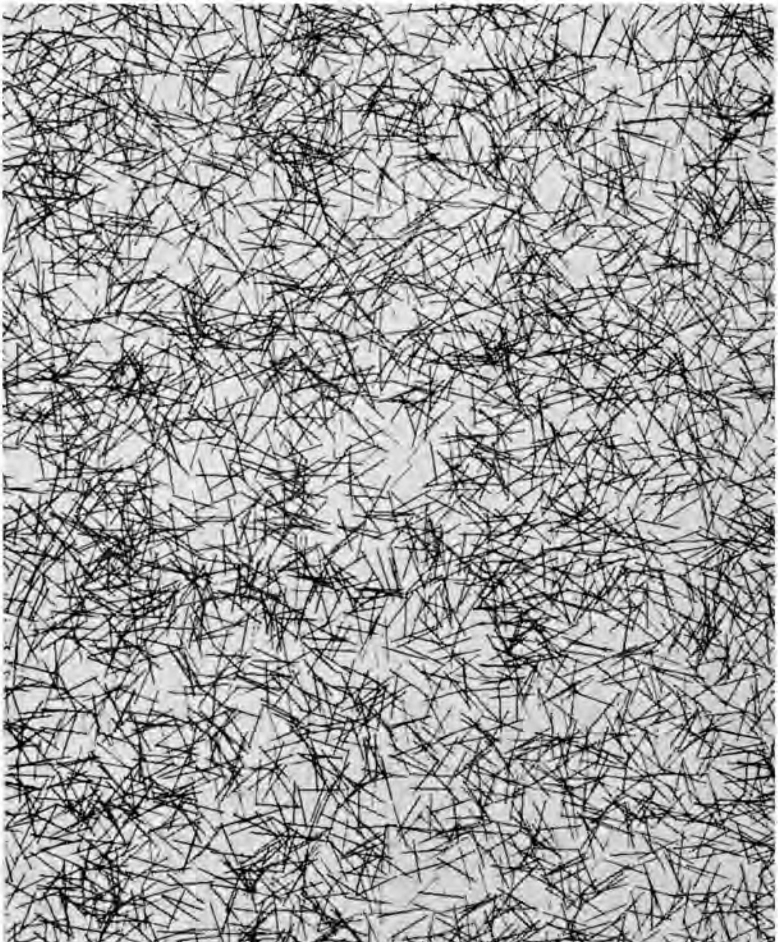


Fig. 28—A computer-drawn random array of lines with a length/diameter ratio typical of an unrefined kraft pulp

deposited fibres and free slurry is very diffuse, that there is a gradual consistency gradient in fact. It is likely therefore that one end of the fibre extends into a higher consistency, thus stronger part of the network structure, while the other is still in the weaker network of the free slurry. When relative motion occurs, therefore, the fibre is preferentially oriented in the direction of relative motion, being held at one end by the network of the deposited mat.

The importance of relative motion between forming mat and free slurry is now evident. It is the most effective way by which the relative spatial relationships of the fibres can be influenced, since it occurs at the moment when further motion is prevented by deposition in the mat. It provides the shear forces necessary to break up flocs and, unlike the shear forces of turbulent fluid flow, it does not provide a means as well for bringing the fibres back into flocs immediately afterwards.

The deterioration of the sheet formation from wire side to top is due to the progressive decay of the relative motion as the sheet builds up. Even the attempts on some machines to apply shake mostly at the dry end are largely defeated by the greater resistance to motion of the fibre network as water is removed. In this zone, the dandy roll has proved the most effective way of introducing relative motion to the upper layers.

It is frequently stated that the well-formed sheet is one in which the fibres are well dispersed and randomly oriented. The statement usually goes on to say that this may be achieved by a high degree of micro-turbulence in the slice jet and that, once achieved, it should be frozen as fast as possible without further disturbance. I would like to question this. My final figure, Fig. 28, is of such a sheet—produced by a computer laying down fibres at random and randomly oriented. It is completely adirectional, as we have checked by orientation studies. It shows gross flocculation effects, even though the fibres' positions were determined randomly. Maybe the ideal sheet consists, instead, of a layered structure, as found by Finger and Majewski, in which the individual layers are ordered structures and not random ones. The technical problem to be solved, therefore, is to develop a process that will do this in such a way that control may be exercised over the relative thickness of each layer, also over the degree of ordering in each layer. To which the mill management no doubt will add, "and do it at a higher speed than competition".

Acknowledgement

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Transcription of Discussion

DISCUSSION

MR. J. MARDON: I have a graph to contribute to the matter in hand (Fig. D18). The relationship between the distance one must have the perforated roll from the slice to avoid a wake effect, the solidity or open area of the roll, the hole size in the roll and the velocity of flow through the slice are given in this diagram.

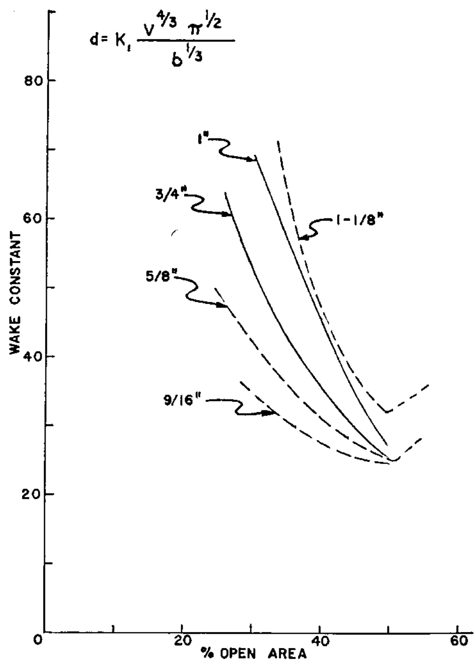

Fig. D18—The relationship between perforated roll hole size and open area and the wake constant

In the formula given on the graph—

d = distance (in inches) the roll must be placed from the slice to have no wake effect at all,
K_1 = wake constant,
π = hole diameter (in inches),
V = velocity (in ft/sec) of flow through the holes,
b = roll diameter (in inches).

Firstly, on the suction box experiment, I would respectfully submit the suggestion as well as the explanation that the table rolls were improving the formation. There is the other possibility from the same evidence that the configuration of suction boxes and so on used might have actually made the formation worse. I have made paper with special suction boxes without this particular effect that we saw in Wrist's paper being noted.

One small point in nomenclature. The term composite profiles was used in this paper, but *superimposed profiles* would be the term that follows from Gavelin, who first used this particular method of analysing beta-gauge profiles.

The next point is that there is reference in the paper to Sir Geoffrey Taylor's first theory, but no mention of his second theory as laid out in the 1958 Montreal paper and the proceedings of the Royal Society, which I think is very relevant. There are those in the field of study of table roll drainage who feel that the suction theory of table roll drainage that involves turbulent flow is in fact more applicable.

A reference to Truman and myself in the paper that we do not recognise the inversion curvature is not correct, as it is plain for anyone to see. We did not believe this to be a major cause of spouting, however, and Sir Geoffrey will deal with this later. I make the point that this inversion of curvature will work to give spouts, if the flow is level, only provided there is a velocity difference in the depth of the stock with the bottom going more slowly. In order to do this, you have to postulate frictional considerations that will slow down the stock.

I feel a little disturbed about the considerations for the energy power consumption in the couch. On faster machines, I think the power consumption does not go up quite at the rate that has been suggested and the force that produces the suction is, in fact, according to Sir Geoffrey's theory, the velocity of the stock from the slice.

As a further point before I get to two practical ones, in the treatment to formulate drainage resistance (under *Formation theory*), the very mystic words Kozeny-Carman appear again. Shoumatoff and I some years ago really first started to take issue on the Kozeny-Carman equation and it would need much more thought before I could properly discuss the particular way it was treated here, but it really does depend in the last analysis on the idea of the capillaric model and I think it therefore not too appropriate for our purposes. Perhaps the preferable approach for better roll drainage is to make special machines capable of giving high drainage rates. There is a real need to show that results from the Kozeny-Carman equation carried out over long time intervals can be transferred to the papermachine working at much higher consistencies and over very short time intervals.

If one takes the theory of flow based on the flow past cylinders at rightangles to the flow, then I submit one is in fact getting into the realm of turbulent flow.

I have now got two practical points to finish off with. In how many machines is the stationary cylinder in the slice actually operating at the moment? I would like to point out that the Macdonald shake is extraordinarily effective, which suggests that shake under conditions in which the stock is relatively concentrated can be really effective.

MR. P. E. WRIST: Mardon's design data for holey rolls will be interesting to those who must make such decisions. As I pointed out, information on this subject is not very widespread nor simple to tabulate, since the wake effect is in practice only one of the factors involved in roll selection.

The suggestion that the suction boxes in the experiment referred to may have made the formation worse is a difficult one to answer, since there is no ready method of determining what it was in the head box. We do know that the reintroduction of one or two solid rolls ahead of the boxes, with their accompanying agitation, substantially 'restored' the formation. We have also practical experience of cases in which replacing grooved rolls with solid rolls has improved formation. A certain degree of agitation during the forming period is definitely conducive to better formation. I have no evidence to prove that good formation cannot be produced over suction boxes, although I do believe that the majority of present day head boxes would not be suitable for such a case.

I suggest that this discussion is not the appropriate place to pursue the mathematical details of table roll suction theory. We are all in agreement that suction occurs, that it produces drainage, also that it causes wire wrap. We are further agreed that the curvatures produced in the paths of the wire and the stock over it are the cause of stock instability. Our concern today is with the results of these disturbances on the structure and formation of the sheet of paper.

In discussing the power consumption by a table roll, I reported the results of a carefully conducted experiment, repeated and confirmed several times. The results may not entirely be as expected and my interpretation of them is still unproven; however, I have no reason to disbelieve the results and would prefer to bend theory to fit them rather than *vice versa*.

I am not a defender of the Kozeny-Carmen equation as you will see both in my paper and in my contributions to the discussion during the week, nor do I share your zeal for special machines to simulate machine operation. I am still hopeful that a solution is possible in terms of conventional filtration concepts. If this is so, we will be able to take account of machine changes by calculation instead of by adjustment of our testing method.

I cannot say how many machines operate with the turbulence generators shown in Fig. 2: I know of several. Your comments on the Macdonald shake are interesting. Incidentally, this shake has its maximum amplitude about two thirds along the wire section, although on the installation I have seen the early table contained several dandy type table rolls. Any shake at a position in which the stock is sufficiently fluid to respond will be beneficial to formation. This type of shake, however, has not attained much popularity.

SIR GEOFFREY TAYLOR: My comments are—

1. The model that yields the result that the maximum suction is $\frac{1}{2}\rho U^2$ is one in which there is no turbulent mixing of the streams coming from below the wire and the space between the roll and wire is flooded. If there is complete turbulent mixing, as one might expect and the space below the wire is flooded, the suction may rise above $\frac{1}{2}\rho U^2$ to a value up to $1{\cdot}4(\frac{1}{2}\rho U^2)$.

If the space is not flooded, any cavitation will reduce suction. It seems to me likely that both turbulence and cavitation occur and, if the suction is found by measurement to be about $\frac{1}{2}\rho U^2$, it is quite as likely to be due to a combination of the two.

2. With regard to the effect of curvature of the wire on the stability of the fluid above it, there are two quite independent effects. If the acceleration is centrifugal (as it is when the wire curves downwards), the free surface is unstable whatever the distribution of longitudinal velocity in the fluid may be. On the other hand, flow is unstable under the action of centripetal acceleration, only if the bottom layer of fluid is moving more slowly than the rest independently of the condition of the surface. At the same time, the free surface is very stable under centripetal acceleration so that any disturbance that grew during the centrifugal stage will oscillate stably so long as the centripetal acceleration is maintained. If it is maintained for half a period of this highly stable oscillation, the surface irregularity is reversed, crests becoming troughs and *vice versa.*

I can see no obvious reason that there should be sufficient variation of longitudinal velocity through the depth of the fluid to give rise to appreciable instability in the centripetal stage.

The effect of alternating stability and instability of a fluid surface oscillating vertically can be seen when a fluid in a container stands on a vibrating surface and Ursell and Benjamin have analysed this case.

3. I agree with Mardon that, according to a theoretical picture of the drainage process, the power required for drainage is derived from the kinetic energy of the fluid above the wire.

MR. WRIST: I do not think we are in conflict with Sir Geoffrey's remarks on the table roll drainage mechanism. He has derived two solutions. One was based on the concept of an ideal liquid and this gave a suction profile closely approximating some experimental curves that Burkhard and I obtained. The second was based on the concept of complete mixing in the nip, which gave a suction profile that predicted suctions 40 per cent greater than we observed. We are both apparently convinced that neither solution has adequately described the problem and I agree that it is apparently a coincidence that the first theory should approximate the experimental curve. In this light, I use the equation of the first theory not because I believe that this theory correctly describes the physical problem, but simply that it provides a good empirical fit to my measured data and, as such, facilitates analysis.

The so-called *post-roll spouting* is a very interesting problem and one that is the subject of a continuing TAPPI-sponsored project at the University of Michigan under the direction of Prof. C. S. Yih. The observed reversal of ridge and trough pattern at the start of this phase is now very well documented, as is also the very rapid growth rate of the instability. Observation does not, I consider, suggest that this motion is a stable oscillation, resulting from a growth pattern in the first phase over the table roll. In this, I think Sir Geoffrey has misunderstood my comments. On the contrary, I wished to suggest that perturbation energy continues to be generated in the second phase.

DR. A. A. ROBERTSON: I would like to ask for further comment on Fig. 12, which relates the plug yield stress to the consistency. The plotted points are based on changes of slope in the pressure drop curves, which have been demonstrated(11) to be due to laminar-turbulent transitions in the wall layer. The breakdown of the plug is not necessarily coincident with this transition.

MR. WRIST: This raises a question that has concerned us somewhat. The assumption inherent in the derivation of Fig. 12 is that the yield shear stress of the plug is equal to the wall shear at the first inflection point of the friction factor curve. Two effects occur in this general Reynolds number range—the boundary layer becomes turbulent and the plug begins to break down at the outer surface. There is no obvious reason for these two events to coincide at this transition point, if indeed they do. We have reason to believe they occur reasonably close together, possibly because the pulp properties control the growth rate of the annulus, hence its transition to turbulence. We are attempting, however, to develop the theory further and to resolve this doubt. We would prefer, for instance, to derive our pulp characteristic parameter from the whole curve rather than from a single point, since the transition is often a gradual one.

MR. D. ATTWOOD: In the paper, a correlation is mentioned between slice opening and basis weight. We have done this and found an amplification factor—that is, if the slice opening is changed by 1 per cent, the profile is changed not by 1 per cent, but by something very much greater. This, I suggest, can be explained by differing retentions on the wire and it is this change in retention that affected the profiles in the experiments you have described with the suction boxes replacing the table rolls. Although you do not give the fact in your paper, when this experiment was carried out, the retention on the wire increased considerably with the suction box arrangement and the consistency in the wire pit fell to a very low value. I regard this as a better explanation of the more stable profiles than that diffusion takes place over the table to any extent.

MR. WRIST: The amplification factor in the correlation between slice opening and basis weight variations is a very important effect and is why slice lips should be maintained as free from distortions as possible. I do not agree with your suggestion, however, that the amplication factor results from different retention rates over the wire. The retention rate is certainly influenced by the basis weight of stock on the wire, but the rate changes quite slowly with basis weight in the practical range and a 1 per cent heavier slice flow would not be sufficient to produce, say, a 3 per cent heavier streak in the final sheet as a result of differential retention alone.

I believe the explanation lies instead in the fact that, when a slice is opened up over a narrow region, the extra flow required is drawn from a wider zone of the flow approaching the slice. In so doing, cross-flow components are created in the slice flow, directed towards the centre of this more open point. These cross-flows continue to act outside the slice and to pile up stock in line with the wider opening and, at the same time, to deplete the stock adjacent on each side of the streak.

The oldtime papermaker, restricted to the use of non-adjustable slice gates, made excellent use of cross-flow components to adjust his weight profile. If he experienced a light streak at one point across the machine, his practice was to place an obstruction on the head box floor, a short distance behind the slice. The presence of the obstruction (an old brick or metal block) created a wake in which the flow had a cross-component in towards the mid-line. These flows, continuing over the Fourdrinier, eventually built up the profile in the lee of the obstruction. The sensitivity of the magnitude of these cross-flows to the location of the obstruction behind the slice was used to advantage in correcting the profile, for by adjusting the distance the papermaker had a method of controlling the amount of 'fill in'.

Your reference to the very different total retention rates provided by the table rolls and the suction boxes is correct. This results from the much gentler drainage rate over the suction boxes. I know of no practical experience, however, to confirm that the retention rate *per se*, under otherwise equivalent table arrangements, has a marked influence on profile uniformity.

A DELEGATE: There is a point that might be clarified. Wrist has just shown us a diagram of random lines demonstrating that you can get concentrations and open spaces; Steenberg this morning defined a floc as being an aggregation of fibres and a semi-rigid body. Is there any means of distinguishing by looking through a sheet whether a clump is due to random arrangement of fibres as shown by Wrist and others or by the simple flattening out of one of Steenberg's flocs?

MR. WRIST: Andersson's earlier statement of disbelief in the existence of flocs in a sheet of paper was undoubtedly dramatic: to a large extent, I sympathise with his viewpoint. In a pulp suspension under appropriately low flow rates, aggregates of fibres can be observed to maintain their identity for a long period of time, to have a definite boundary around them and to roll along like balls. They are truly flocs. In shear and turbulence, they begin to disintegrate, their boundaries become less definite so that momentarily it may be hard to define the exact demarcation of flocs. Eventually, the aggregation becomes a random transient process. In a sheet of paper, the concept of discrete flocs is similarly untenable. Boundaries are ill-defined and fibres may extend through two or more zones of concentration. In terms of Steenberg's definition, the paper sheet is strictly a single floc with local density variations. I have purposely ignored stock lumps in this description. These consist of tightly knitted bundles of fibres caused by incomplete fibre makedown or from stapling and spinning actions over obstructions in the flow. Their identity is usually readily traceable in the final sheet.

If we are prepared to accept a more liberal interpretation of the word *floc*, however, as applied to a sheet of paper, it is natural to speculate whether any correlation exists between the zones of density fluctuation in the finished sheet and the aggregations that occur in the head box. If such a correlation does exist, then there would be a basis for recognising a floc structure in a sheet of paper. On slow running machines, I have no doubt that relatively stable flocs are formed in the head box, that they pass on to the wire and are partially blended in the final sheet along their boundaries, without completely losing their individual identities. The presence of a chemical flocculating agent in the system enhances this correlation. On high-speed machines, fed by a turbulent slurry, the situation is less clear cut.

The existence of stable flocs in the head box itself is doubtful and it is more probable that the local concentrations that do occur are the result of transient random processes. Over the forming zone and in the final sheet, random deposition and flow disturbances are more probable causes of the density fluctuations than are flocculating effects. Under these circumstances, I believe Andersson is justified in his rejection of the floc concept to describe paper. There will obviously be many cases in which both effects occur simultaneously.

Mardon suggests that a papermaker can distinguish between true flocs and random statistical fluctuations and, particularly in the extreme cases, I agree that this is probable. To distinguish between the two effects on a numerical or instrumental basis is not possible at present. The means are probably already available, once we become more skilled in our interpretation of the frequency distributions or correlogram diagrams now available with recent formation testers.

DR. R. DE MONTIGNY: I should like to refer to the concluding remarks in Wrist's paper, in which he suggests the probable desirability of constructing a sheet of paper from a number of ordered layers rather than aiming for a homogeneous structure of fibres uniformly dispersed and oriented in all directions. In this context, it might be of interest to mention some work that Stone and I have been carrying out at the Research Institute in Montreal during recent months. We have developed a laboratory device that, although not yet entirely to our liking, enables us to produce handsheets with a high degree of fibre orientation. Depending on the type of fibre, from 75 to more than 90 per cent of the fibres can be aligned at $\pm 10^\circ$ to the main sheet direction.

These sheets have interesting properties that can be easily predicted—after they have been measured. Of even more interest are composite sheets made up of a number of such oriented sheets wet-pressed together with the fibres in each ply at some angle to those in adjacent layers. For example, a two-ply sheet with fibres crossed at 90°, when tested in one of the two main directions, shows between four and five times the tearing resistance and between three and four times the folding endurance of a standard random handsheet. When tested at 45°, tearing and folding strengths are still very high, tensile strength is low, but elongation extremely high. We have examined briefly a number of multi-ply sheets made up with varying relative orientation of the component layers and these indicate that a wide range of combinations of physical properties differing widely from those of random sheets can be achieved.

I should like to point out that this work was not undertaken with the objective of commercial production of such papers, since obvious and very formidable technological difficulties lie in this path. We feel, however, that such laboratory-made papers, built up of oriented layers, just as Wrist has visualised them, might provide useful models for the study of the relations between the structure and properties of paper and we propose to pursue our work in this sense.

MR. WRIST: This concept is certainly a most interesting one. It confirms our own impression that a papermachine that will make a multi-ply sheet with controlled orientation in each ply would offer new possibilities.

Finally, a word of caution to anyone contemplating drawing random lines on a sheet of paper. Before going too far, I suggest you carefully check the randomness of your tables. The figure I show was based on the Rand Corpn. tables as given in the appendix to *Introduction to Statistical Analysis* by Dixon and Massey. As we proceeded further to sheets of higher density, we began to observe a regularity appearing. On checking the tables for the frequency of occurrence of digits, we found them to be non-randomly distributed and that the even digits were more abundant than the odd. This gave us regularly spaced banding, observed in both directions at the even-numbered positions. A similar check on the Fisher & Yates table of random numbers gave a similar non-random distribution of digit frequencies, the even numbers again predominating. Most recently, we have tried to use one of the random number generators, suggested by I.B.M. Corpn. This has given us a most unusual non-random array. We are still looking for a truly random set of random numbers.

Written contributions

MR. W. VAN DE MEER: The influence of air carried around the breast roll on the trajectory of the jet was measured on one of our machines running at 300 m/min. The free length of the jet was 70 mm. The mean air pressure under the jet was 4 mm water gauge. Since the jet was 12 mm thick, the influence of gravity was only two thirds of the normal value of g.

The gap between pairs of holey rolls is of great influence. The resistance of the rolls can cause pressure drops across them of up to 50 mm water gauge. This pressure creates high speed flow through the nips. With a 5 mm gap for a 150 mm roll, the by-pass flow can be as high as 20 per cent.

Stock lumps are formed whenever there is a difference in speed between the surface of the roll passing close to a boundary and the flow along the boundary. The lumps form on either the front or back edge of the holes according to the relative velocity difference.

It is my opinion that it is the dimensions of the land between the holes, rather than the hole size, that has the most influence on lump formation. We had good operation with a bleached sulphate furnish with 16 mm diameter holes on a 24 mm pitch, but had trouble with the same hole size on a 21 mm pitch. Likewise, on newsprint, a 6 mm land width was satisfactory, but a 4 mm land gave trouble.

Our experiments show another cause for streak formation. The jets coming from the holes in the roll near the front slice wall impinge on the wall. The flow along the wall creates a boundary layer of water and crill, which gathers between the jets into a stable streak of lower consistency. The problem is to break up these streaks by attacking the boundary layer. The difficulty with a construction such as Fig. 2*b* of the paper is that it is liable to cause slime and dirt problems. We do not have the answer yet.

The importance of table roll stock jump in promoting good formation is widely known. The action of the rolls is made more stable, if the end of their suction zone is defined by a fixed boundary such as is provided by a wire supporting baffle close to the roll.

Finally, two questions—how is the Reynolds number in Fig. 2 defined? —and did fibres not collect around the $\frac{1}{8}$ in impact rod in Fig. 6?

MR. WRIST: I agree with Mr. van de Meer's comments on the importance of the land between the holes in a holey roll. My paper did not cover all aspects of holey roll operation. The wall thickness is another equally important factor. The specifications for a holey roll must take all these factors into consideration and cannot therefore be reduced to a simple formula or graph.

The Reynolds number of Fig. 2 is based on the viscosity of water and we used the impact rod in water alone, fibres would certainly have caused problems.

MR. B. I. HOWE: The formation profiles in the cross-direction of two grades of newsprint made at different speeds on the same machine show a number of discontinuities (Fig. D19). A serious wake effect was troubling the operation of this machine, owing to the location of the perforated rolls near the slice. The streaks from these stable wakes can be seen on the right side of the profiles as the deflection in the micro-scale.

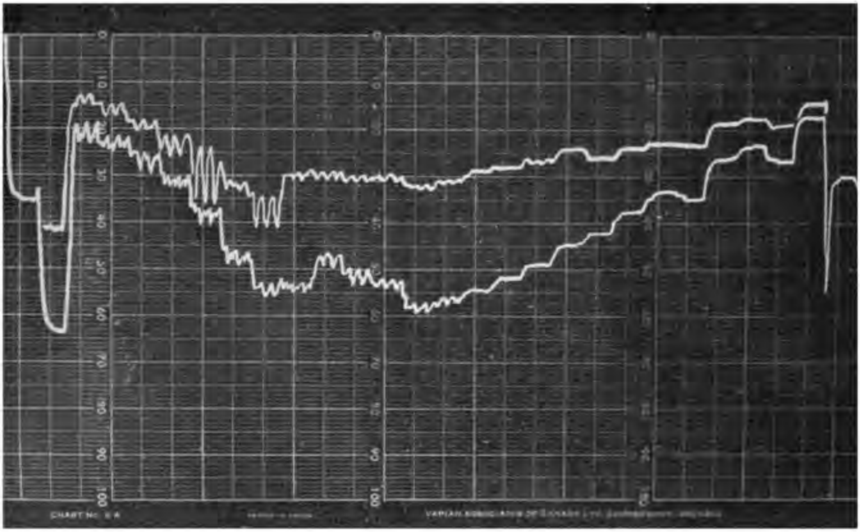

Fig. D19

The streaks have remained in the same position despite the difference in speed at which the two sheets were made and the much improved formation level of the lower profile is the sheet made at the lower speed.

The difference in wire mark at the lower end of the left side of the profiles illustrates the effect of additional calendering. The only difference in surface finish techniques between the two sheets was three additional nips of the calender stack on the sheet with the better (lower) formation profile.