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WET END FACTORS AFFECTING THE UNIFORMITY OF PAPER

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Summary

The measurement of paper uniformity is discussed with special reference to those methods providing information that may be used to investigate the sources of variation of structure and properties. The flocculation of fibres in the stock and the hydrodynamic properties of the head box are shown to be the major causes of heterogeneity.

Fibre flocculation is both a direct source of heterogeneity and a factor affecting the fluid mechanical properties of the stock. The flow properties of fibre suspensions are described on the basis of pipe flow studies and the significance of these studies to head box flow is discussed.

The head box is considered as a source of non-uniformity with some reference to the significance of secondary flows. Experimental methods are described that may be used to assess head box performance to investigate conditions that give rise to poor uniformity.

Areas in which further research is desirable are indicated.

L'influence du fonctionnement de la table plate sur le degré d'homogénéité du papier

Les auteurs traitent de l'expression quantitative du degré d'homogénéité du papier, en étudiant spécialement les méthodes dont les résultats peuvent révéler l'origine des variations de la structure et des propriétés du papier.

Le manque d'homogénéité dans le papier dépend principalement de la flocculation des fibres dans la suspension et des conditions hydrodynamiques dans la boîte de tête.

La flocculation est à la fois une des causes principales de *l'hétérogénéité dans le papier et un facteur qui influe fortement sur les propriétés fluides de la suspension.*

D'après certaines études d'écoulement dans les tuyaux de suspensions de fibres on déduit leurs propriétés et on traite de l'importance de celles-ci dans l'hydrodynamique de la boîte de tête.

On considère la boîte de tête en tant que source d'hétérogénéité en traitant sommairement de certaines perturbations hydrodynamiques secondaires.

Les auteurs exposent des méthodes experimentales pour évaluer le comportement de la boîte de tête et les conditions donnant lieu à un manque d'homogénéité.

On indique certains domaines dans lesquels de nouveaux recherches seraient utiles.

Faktoren in Stoffzuführung und Nasspartie beeinflussen die Gleichförmigkeit des Papiers

Es wurden die Methoden zur Messung der Gleichförmigkeit von Papier im Hinblick darauf untersucht, dass man sie zur Aufdeckung der Ursachen für die Veränderungen von Struktur und Eigenschaften heranziehen kann. Es zeigte sich, dass die Ausflockung des Stoffes und die hydrodynamischen Eigenschaften des Stoffauflaufes vorherrschend zur Heterogenität beitragen. Die Ausflockung ist nicht nur direkt verantwortlich für die Heterogenität, sondern beeinflusst ausserdem die mechanischen Eigenschaften der Stoffströmung. Die Strömungseigenschaften der Fasersuspensionen können mit Hilfe von Studien an Strömungen in Rohren beschrieben werden, wobei die Signifikanz dieser Studien mit der Strömung im Stoffauflauf diskutiert wird. Da der Stoffauflauf im Bezug auf die Signifikanz der Sekundärströmungen als Ursache für die Ungleichförmigkeit angesehen werden kann, wurden experimentelle Methoden beschrieben, mit denen man die Bedingungen im Stoffauflauf zur Erzielung einer besseren Gleichförmigkeit feststellen kann. Abschliessend wird über die Gebiete berichtet, auf denen weitere Forschungen erwünscht sind.

Introduction

THE properties of a sheet of paper vary from point to point. The lack or uniformity is apparent when any of the multitude of tests available for paper evaluation is repeated on different areas of the same sample or on several samples taken from the same machine production at different times of positions. In order to proceed to an examination of the nature of this heterogeneity and its causes, it is convenient to draw a distinction between small-scale and large-scale variations. A basis for this differentiation can be found by comparing the evaluation of uniformity by *formation* or *look-through* with the measurement of basis weight variation. The former involves fluctuations in a paper property over comparatively short distances, whereas the latter concerns the variation of an averaged property at larger separations.

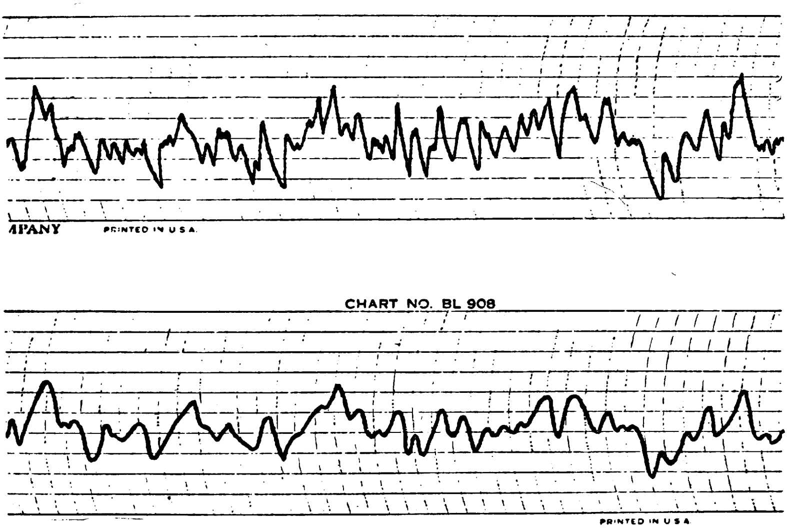

Fig. 1—Recorded light transmission fluctuations obtained by scanning a paper sample: two scanning spot sizes were used—1.25 mm (upper) and 2.5 mm (lower); the scanned length is about 15 cm

For the purposes of this discussion, we have arbitrarily differentiated small-scale variations having a characteristic linear dimension less than 5 cm from variations of larger scale.

The nature of the heterogeneity in paper is most clearly shown when considering properties that can be continuously measured and recorded—optical properties, caliper, tear resistance or mass per unit area. Examination of such records (Fig. 1) shows that the property varies continuously in a more or less random fashion. It has been shown in some previous work[1–3] that much of the small-scale variation in sheet properties is in fact due to a random process of fibre flocculation in the suspension from which the sheet is formed. It has been possible therefore to apply the statistical theory of random processes both to the study of fibre flocculation and sheet uniformity. It has similarly been demonstrated[4,5] that a significant component of the variation in the basis weight of paper is random and is attributed to large-scale turbulence in the head box.

However, all of the processes leading to heterogeneity in paper cannot be considered to be random. Non-uniformity may be traced also to differences in the flow or forming processes across the machine and to isolated, irregular or periodic causes of which machine adjustment, imperfect consistency regulation and vibration are respective examples. These processes primarily affect large-scale variations. Wire and felt marks are examples of non-random, small-scale variations.

The lack of uniformity in properties has several practical consequences. Not only is the appearance of the sheet affected, but, in addition, coating, adhesive absorption, calendering and printing properties are downgraded, dimensional changes with humidity are uneven and lead to cockling. Moreover, the maintenance of uniformity is important in the papermaking process itself. Fluctuations in mechanical properties of the wet web at the couch are a frequent cause of wet-end breaks and may be more significant than the mean level of strength properties. Non-uniformity in structure and weight also lead to uneven drying with consequent impairment of sheet quality.

It is the purpose of this paper to outline the available methods of assessing paper uniformity and to discuss how the uniformity is influenced by the behaviour of the stock in the head box.

Measurement of paper uniformity

General

Although sheet uniformity could be assessed in terms of the variation of any of several properties, the measurement is usually based on the variation of basis weight, if large-scale variations are of interest or on the variation of light transmission, when small-scale variations or formation are concerned. The analysis of heterogeneity is necessarily statistical in nature and is based on the frequency and amplitude of fluctuations in the value of the considered property about its mean value.

Thus, if I is an electric current measuring the instantaneous value of a property (for example, the light transmission at a point) and if the property is continuously measured along some path, I varies continuously. The signal generated can be considered to be a summation of a direct current measuring the average value of the property and an alternating current, which in turn

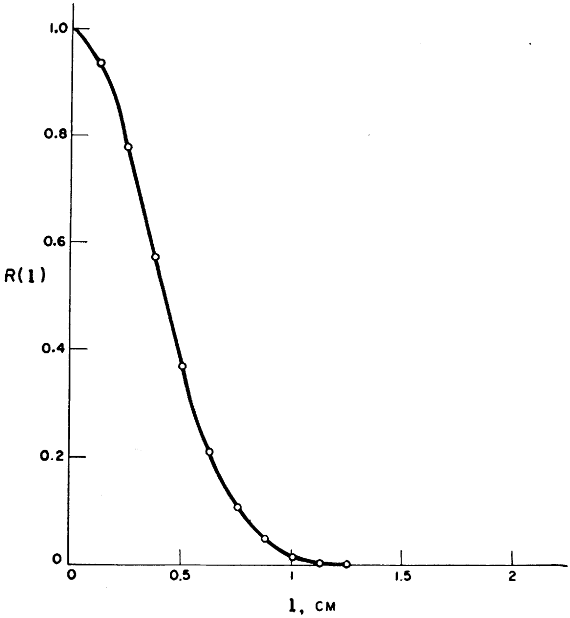

Fig. 2—An autocorrelation curve $R(l)$ of the type that may be obtained by measuring the optical transmission of paper using a 2.5 mm scanning spot[3]

is a summation of fluctuations from the mean of varying frequency, amplitude and phase. The following statistical quantities and functions may be used to describe the signal[6]—

$\bar{I}$ = the d.c. component of the signal, the average value of I along the scanning path,

$\sigma = \sqrt{\overline{i^2}} = \sqrt{\overline{(I-\bar{I})^2}}$ = the a.c. component of the signal, the root mean square value of the fluctuation of I about its mean value $\bar{I}$,

$w(f)$ = the power spectrum, defined so that $w(f)df$ is the fraction of $\bar{i}^2$ due to frequencies between f and $f + df$, where f has the dimensions of length^{-1} rather than time^{-1} and is based on the length along the scanning path,

$R(l)$ = the autocorrelation function, the correlation of pairs of instantaneous values of i separated by a variable distance l along the scanning path—that is, $R(l) = \overline{i(x) \cdot i(x+l)}/\overline{i(x)^2}$

If the signal is random, I and σ are constant if averaged over a sufficient scanning distance, $R(l)$ falls from a value of unity at $l = 0$ to zero at some finite value of l (Fig. 2) and the power spectrum has a regular shape without sharp peaks. Furthermore, the functions $R(l)$ and $w(f)$ are Fourier transforms of one another and thus summarise the same information (Fig. 3).

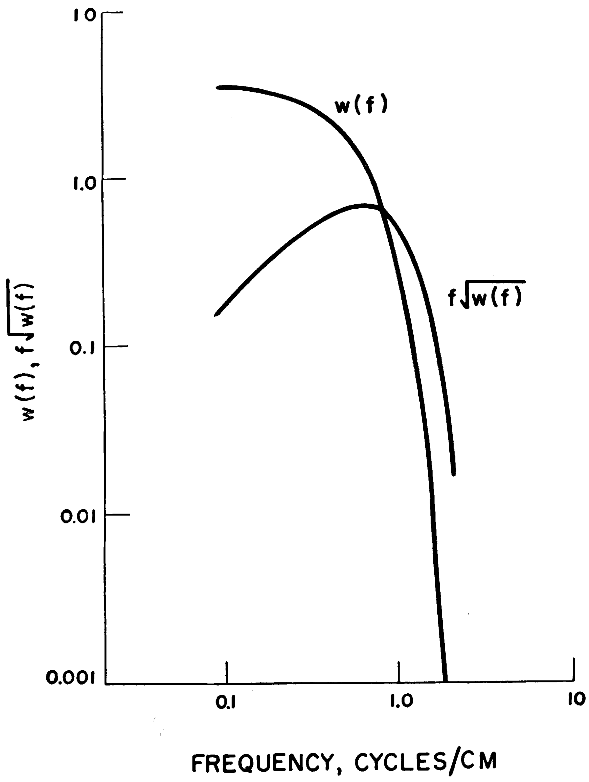

Fig. 3—Frequency distribution curves obtained from the Fourier transform of the curve in Fig. 2, where $w(f)$ is the power spectrum and $f\ \sqrt{w(f)}$ is the frequency distribution that would be given by an analyser measuring r.m.s. values over a band width proportional to the frequency

When periodic components appear in the signal, however, peaks at the corresponding frequencies appear in the frequency spectrum. Their effect on the autocorrelation function is less evident except when the periodic disturbances are of low frequency; in this event, the 'tail' of the curve describes a wave about the l axis, the shape of which is related to the periodic frequencies.

Functions of the type summarised above have been developed and applied in such varied fields as fluid mechanics (turbulence theory),(7) communications (signals and random noise)(6) and oceanography (wave analysis).(8) The analysis of paper heterogeneity is in many respects similar to the problems mentioned and the use of frequency analysis and autocorrelation functions has proved to be of considerable value. Similar applications have been made in analysing the uniformity of textile yarns and in the analysis of various physiological phenomena.

Small-scale uniformity

The small-scale uniformity of paper is normally assessed as *formation.* A qualitative subjective assessment is made visually on the basis of look-through. A number of instrumental methods have been devised to give an objective measurement, some of which are listed in Table 1. In all cases, the sample is scanned with a light source on one side of the sheet and a photoelectric cell on the other. The fluctuating current generated in the photocell circuit results from the varying light transmission of the sheet.

The simple measurement of the ratio of the amplitude of the fluctuations to the mean transmission $\sigma/\bar{I}$ is probably adequate for control purposes, but any investigation of the causes and effects of non-uniformity demands some knowledge of the frequency spectrum of the fluctuations. The highest frequencies usefully measured depend on the size of the scanning spot (Fig. 1) and it is found desirable to use spot diameters as small as 0.1 mm when correlations of formation and printability are sought. At the other end of the scale, it is undesirable to measure low frequencies (less than 0.1 cycles/cm) that are not adequately sampled by reason of limited sample size. These low frequencies are arbitrarily considered to be basis weight variations rather than as components of formation. For this reason, several instruments are provided with low frequency cut-offs.

Procedures for weighting the data on the basis of the psychophysical response of the eye permits an instrumental measurement that is similar to visual judgment,(10,17) although it is not possible to take into account the acuity of the eye in perceiving patterns. Two instruments(15,18) are particularly useful in investigating machine operation, because they permit independent scanning in the cross- and machine-directions of the sample. The identification of periodic variation in structure is therefore possible and may facilitate tracing the defects to their source. This feature has been especially useful in studies related to wire mark.(18)

TABLE 1—FORMATION MEASUREMENT

Year	*Author*	*Ref.*	*Scanning*	*Measurement*		*Investigations*
1935	Davis, Roehr, Malstrom	9	Random helical	Amplitude	*C*	Flocculants + deflocculants,[39] visual grading[89]
1952	Favis, Robertson, Mason	1	Helical	Amplitude & recording	*R*	Theory, fibre type, concentration, fibre length, viscosity, sedimentation, basis weight
1952	Brecht, Wesp	10	Circular	Amplitude & frequency	*C*	Fibre type, concentration, beating, fibre length, visual grading
1953	Glover, Rance	11	Random helical	Amplitude	*C*	Stock concentration, deflocculants, strength
1955	Wiggins, Teape	12	Machine	—	*C*	—
1955	Williams	13	Machine	Amplitude	*C*	Freeness, consistency, stock/wire differential, strength
1956	Robertson	3	Random helical	Amplitude & autocorrelation	*R*	Theory, visual grading
1956	Jamison (Allegany)	14	Raster	Amplitude	*C*	Printability
1956	Alston, Goodhew, Chapman	15	Directional	Amplitude	*R*	Visual grading
1960	Balmasov	16	Circular	Amplitude & frequency	-	—
1960	Andersson, Sundewall	17	Circular	Special	*R*	Visual grading
1960	Burkhard, Wrist, Mounce	18	Directional	Amplitude & frequency	*C*	Wire mark, printability, visual grading
1960	Westra	19	Strip	Amplitude	-	Concentration, sedimentation, basis weight, visual grading

NOTE: *C* = available commercially

R = research instrument only, not available commercially

The measurement of formation by optical means has the obvious limitation that it is measuring only transmission fluctuations, whereas, except for appearance, greater significance is in practice attached to caliper or to substance-weight fluctuations. A calculation of mass variations based on optical scanning data obtained using a scanning spot 3 mm $\times$ 3 mm has been reported.[19] The values of the coefficient of mass variation range from 0.72 per cent for a uniform writing paper to 9.27 per cent for a facial tissue. However, correlation of light transmission variation with mass variation is imperfect and may even be negative in heavily calendered sheets. In spite of this limitation, optical formation measurement remains useful in that it is a convenient and valid measure of sheet heterogeneity. The measurement of small-scale substance variation by the use of α,[20] β[21] or γ-radiation from radioactive sources has been suggested and used in special circumstances.

The optical measurement of sheet uniformity is not restricted to paper and similar methods have been applied to plastics[22] and to the problem of graininess in photographic film.[23]

Large-scale uniformity

The measurement of basis weight variation has been carried out by cutting and weighing samples taken from machine production[24] and plotting cross- and machine-direction profiles or calculating variance. A similar result is more commonly and less arduously attained by the use of more or less automated gauges based on the measurement of basis weight by the relative transmission of β-rays.[25] The sheet area instantaneously measured is commonly 3–4 in^2. The gauge may be mounted on the machine, with or without facilities for traversing and used for recording or for machine control. In other versions, a strip or multiple strips of paper cut across the reel are fed through the gauge and the basis weight profile is recorded.

Analyses of basis weight profiles have been reported by several workers. A computer has been described[5] that provides an automatic numerical measure of cross-machine variance in basis weight and thus avoids graphical analysis.

The data obtained from multiple basis weight profiles across the machine may be subjected to variance component analysis to give values to the cross-direction variance, machine-direction variance and the random variance.[4] The first is a measure of stable machine-direction streaks, the second of the effect of such causes as fan pump and stock system variations, which affect all points across the machine equally, whilst the third, the random component, is attributed to turbulence and unstable flow conditions in the head box. The detection of cyclical variations in the machine-direction using autocorrelation analysis has been discussed.[4]

Causes of non-uniformity

THE lack of uniformity in a paper sheet has its origins throughout the papermaking process, but chiefly in the stock system and inlet and on the wire of the papermachine. Control and improvement of uniformity can be expected by application of the principles of fluid mechanics together with a knowledge of the physics of papermaking fibres suspended in water and with the benefit of the empirical results of practical papermaking. The basis weight variance and the formation characteristics of the sheet are the criteria commonly accepted for evaluation of uniformity. These criteria can serve also to evaluate the character of the stock and the performance of the machine.

It is well to recognise, however, that lack of uniformity is often caused, not by the fluid mechanical properties of the stock or the hydraulic features of the head box, but by mechanical or operating defects. The effects of a malfunctioning distributor roll have been reported[24] and attention has been drawn to the role of the slice profile and the variation of the profile with temperature and the flow of stock.[4,26] Sheet variations have been traced to vibrations affecting the head box,[27] while other variations have been attributed to deficiencies in whitewater circulation and to faults related to the screens, fan pump, apron, wire, table rolls, dandy, showers, felts and doctors.

The attention of the authors was recently drawn to the prevalence, in a variety of sheets produced on different Fourdrinier machines of stable, regularly spaced basis weight streaks in the machine-direction with approximately 2 in separation. Several suggestions about the possible sources of the defect have been advanced, including the mechanical properties of the slice and wire and the spacing of wire showers as well as the hydrodynamic properties of head box fittings and the possibility of slice jet instability. The similar behaviour on a wide variety of machines (Table 2) is of interest in view of the differences in equipment and operating conditions and has so far not been satisfactorily explained.

It is also pertinent, in considering the sources of non-uniformity to point out that there is a limitation on the uniformity that may be achieved simply because the sheet is formed from small elements of random orientation and position. If it is assumed that a sheet could be formed by the random deposition of individual fibres on a plane without interaction, the sheet so formed would have substantial variation in substance from point to point. For example, assuming a basis weight of 50 g/m², a uniform fibre length of 3 mm and 6.6×10^6 fibres/g, the coefficient of variation of mass of fibre based on areas of 1 mm² is calculated to be about 3 per cent (Appendix).

TABLE 2—STEADY STREAK SPACING IN NEWSPRINT FOURDRINIER MACHINES

	Mill and machine	*Speed, ft/min*	*Reel width, in*	*Flow eveners*	*Head box*	*Streak spacing, in*	*Streak amplitude*(a)
1	A1	1 630	227	No	Closed	2.21	Large
2	A1	1 600	227	No	Closed	2.13	Large
3	A1	1 643	227	No	Closed	2.38	Large
4	B1	1 000	146	Yes	Open	2.16	Large
5	B2	1 362	146	Yes	Open	1.90	Medium
6	B3	1 270	146	Yes	Open	1.82	Medium
7	C1	1 785	219	No	Closed	2.39	Small
8	D1	1 880	218	No	Closed	2.25	Small
9	E1	1 776	226	Yes	Open	2.20	Medium
10	F1	1 200	146	No	Closed	2.16	Medium
11	G1	1 960	216	Yes	Closed	2.41	Small
12	H1	1 350	227	Yes	Open	2.20	Medium

(a) Large, medium and small refer to fluctuations in basis weight in a 32 lb sheet of above 1 lb, 0.5–1.0 lb and below 0.5 lb, respectively, based on an area of 1 in × 3 in

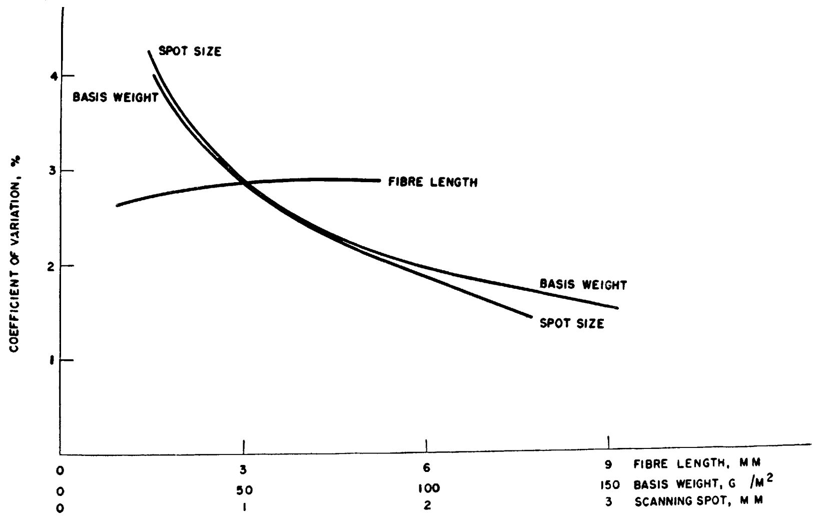

Fig. 4—The coefficient of variation of mass in an ideal sheet when the values of the fibre length, scanning spot size and basis weight are varied from 3 mm, 1 mm and 50 g/m², respectively (*see* Appendix)

This variation increases with an increase in mean fibre length, decrease in basis weight or decrease in the 'scanning spot' dimension (Fig. 4).

A handsheet formed under conditions approximating to those specified has been found to have a coefficient of mass variation approximating to that calculated.

Some relevant properties of pulp suspensions

Degree of flocculation

General

THE flocculation of pulp fibres at papermaking concentrations—that is, the tendency of the fibres to interact or entangle to form aggregates or network structures—has two significant consequences. Firstly, flocculation leads to local variations in fibre concentration in the suspension that are reflected in the formation or small-scale heterogeneity of paper formed from the suspension and, secondly, the presence and interaction of fibres and aggregates causes the hydrodynamic behaviour of the suspension to differ significantly from the behaviour of water. A fibre floc may be shown to have measurable tensile and shearing strengths[28] and to be capable of undergoing plastic and elastic deformation. In the papermaking process, the formation, distortion, rupture and disintegration of flocs by shearing forces take place.[29] Even at the highest shear rates, fibre dispersion is not complete at papermaking consistencies and fibre interaction and entanglement are still evident. However, at high shear rates, flocculation can be regarded as a dynamic equilibrium process involving the simultaneous dispersion and formation of flocs. This equilibrium is displaced toward greater dispersion by increasing the rate of shear.[2,29]

It is to be expected that the presence of fibre aggregates in suspension will result in fluid mechanical behaviour quite different from that of water. The presence of the fibre structures can provide a mechanism for momentum transfer in addition to the normal viscous or eddy diffusivity effects.[30] In addition, the elastic properties of fibres and flocs might be expected to lead to the cross-stresses during shear that are evident in such phenomena as the Weissenberg effects and various types of secondary flow.[31] These effects have been shown to exist in suspensions of fibres in a liquid of high viscosity,[28] but it is not established whether this behaviour has practical significance in papermaking hydrodynamics.

Measurement of flocculation

The measurement of fibre flocculation and investigation of the factors determining the flocculating tendency of a pulp have been reported using various techniques, including measurement of time required to flocculate a disperse fibre suspension,[32,33] the equilibrium state of flocculation in a dilute sheared suspension measured by optical means,[2] direct tensile strength measurement of fibre flocs at papermaking concentrations,[28] equilibrium state of flocculation in turbulently flowing suspensions,[34–36] measurement of the uniformity of stationary fibre suspensions[37,38] and the measurement of formation of standard handsheets.[1,39]

Factors governing flocculation

The extent of fibre flocculation and the mechanical properties of the flocs vary with the nature of the fibres and their concentration. In general, it has been shown that increasing fibre length and fibre flexibility promotes flocculation by increasing the possibilities of fibre entanglement.[28] The surface properties of fibres may be modified to promote or decrease fibre flocculation—for example, by beating, which increases surface roughness (at the same time, fibre flexibility), by the addition of polymers or vegetable gums or by the addition of electrolytes. The presence of air in the stock is believed also to increase flocculation by the attachment of bubbles simultaneously to two or more fibres.[40]

The role of additives in determining the flocculating properties of a pulp are not fully understood, but three or four possible mechanisms may be considered—

(*a*) The interfibre frictional properties may be altered when the electrical attractive or repulsive forces between the fibres are varied by the sorption of ions, though simple electrolyte systems have been shown to be ineffective and deflocculating action has been claimed only for complex systems such as alum, which produces alumina floc and hexametaphosphate, whose chemistry and action are complex. A variation in flocculation with pH value has been observed,[36] but the variation was substantially reduced when process water was replaced by distilled water in making up the stock.

(*b*) In the case of the sorption by the fibres of highly swollen colloidal material, the mechanical properties of the sorbed material may be such as to reduce the frictional resistance between fibre surfaces superposed on any charge effect that may be present.

(*c*) When highly swollen material exists in the stock in the form of larger particles of micelles, a coagulation of fines about the micelles is possible as a result of entanglement or attractive forces.

(*d*) A fourth mechanism could conceivably result from the mechanical or electrical effects of discrete particles, which by their presence inhibit fibre-to-fibre contacts. The improved formation and increased sheet bulk resulting from additions of diatomaceous earth is a possible example.

These alternative mechanisms are sufficient to explain the experimental observations. Deacetylated karaya gum has been found to be an excellent deflocculant for long fibres, but it acts at similar concentrations as a coagulant for fines.[2] The efficacy of such gums as karaya, guar and locust bean is attributed primarily to their mechanical properties, although other factors also may be involved.

The action of alum in relation to flocculation, thus to paper uniformity, deserves some comment because of the widespread use of this material in mill operations. In addition to its role in dyeing and internal sizing, many virtues are attributed to alum, ranging from microbiological inhibition[41] to correction of pitch troubles.[42] It is not surprising then that it is claimed also to be a deflocculant for fibres and is used as a coagulant for fines. Data on this point[32,43] suggest that its behaviour depends on when and how it is added, its concentration, the pH value of the stock and other chemicals or materials present. Any of the four mechanisms mentioned may be operative, depending on the conditions of precipitation and the degree of dispersion of the alumina floc. Much more research is required, if the relation of alum to sheet uniformity is to be understood.

It is to be noted that the observed effects of additives depend upon the method of investigation. In static systems or in systems in which shearing forces are very small, the observed flocculation changes due to electrical effects may be quite large. On the other hand, when flocculation measurements are made under conditions of turbulent flow or when rates of shear are high, the differentiation of treated and untreated pulps is greatly reduced because of the relative magnitude of hydrodynamic and attractive forces.

Further studies of the role of additives in respect to fibre flocculation are required to determine the most suitable deflocculants and, conversely, to enable the papermaker to avoid additives or chemical components that affect formation adversely. It is generally true that fibre flexibility, flocculation, wet web strength and, to some extent, sheet strength are positively correlated. Thus, fibre properties such as length and flexibility, which are desirable for strength, frequently result in poor formation. A suitable deflocculant permits improvement in sheet formation without impairment of other properties.

Flow properties

The flow properties of pulp suspensions are largely determined by the flocculating tendency of the fibres and are therefore affected by the fibre properties that affect flocculation. Several recent studies[29,30,44,45] have thrown a great deal of light on the hydrodynamics of pulp flow.

When pulp stock from a stirred head box is circulated through a long pipe of circular cross-section, the nature of the flow depends upon the flow velocity (Fig. 5), fibre concentration and fibre properties.[29,30] At low flow rates, the disperse fibres entering the tube entangle to form a continuous network structure. Under these conditions a smooth plug flow results in which the fibre network moves through the tube with the shear borne by an almost clear water layer at the wall (profiles 1 and 2, Fig. 5). At the lowest velocities or in a rough tube, the network that forms may be partially disrupted as a result of frictional contact with the wall and rolling flocs may be formed. At somewhat higher circulation rates, the turbulence at the entry is not completely damped out and a fairly continuous network structure

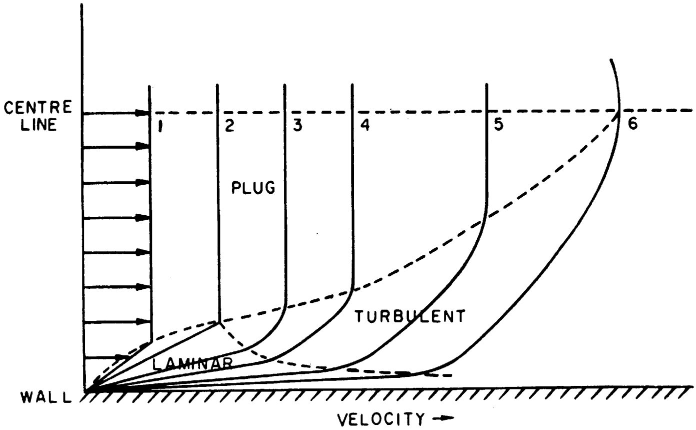

Fig. 5—Velocity profiles in stock flowing in a circular pipe[28–30]—profiles 1 and 2 represent plug flow at increasing flow rates; profiles 3, 4 and 5 represent mixed plug and turbulent flow; profile 6 represents turbulent flow; the vertical scale is expanded near the wall to show the annulus in plug flow and the laminar sub-layer in turbulent flow

forms at the axis of the tube, surrounded by an annulus of turbulent fibre suspension (profiles 3, 4, 5, Fig. 5). At still higher flow rates, turbulent flow is maintained across the whole cross-section (profile 6, Fig. 5).

The transition velocities limiting the regimes of frictional, plug, transition and turbulent flow may be determined visually in a transparent pipe or deduced from measurements of pressure drop, velocity profiles or turbulence.[30] The non-uniformity of the flowing suspension may be measured by optical methods analogous to the measurement of paper formation[29] (Fig. 6). The greatest heterogeneity is measured at the very low rates of flow (*A*), in which the network structure is disrupted by wall friction. When a network structure is formed near the inlet at velocities corresponding to smooth plug flow, the stock is completely flocculated in the sense that the fibres form a single continuous network structure or floc. This floc may be quite uniform (*BC*), if the head box dispersion is uniform and represents a 'frozen flow'. Networks forming at higher velocities and at greater distances from the inlet may be less uniform, the heterogeneity reaching a maximum in the region of transition flow (*D*).

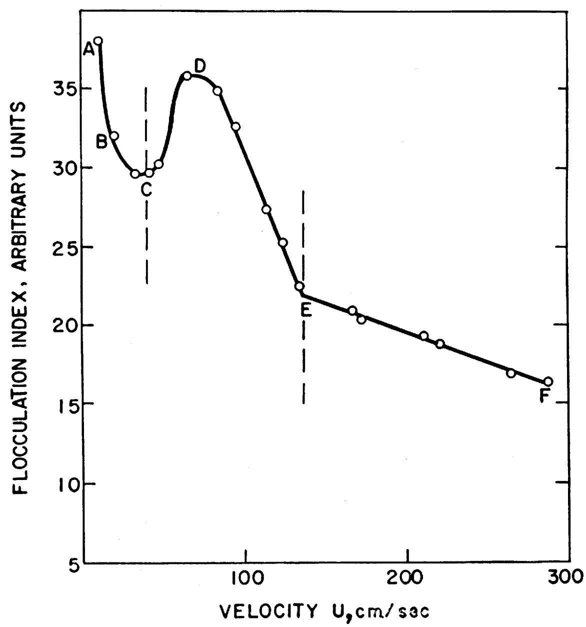

Fig. 6—The flocculation index, an inverse measure of uniformity, of a 0.4 per cent sulphite pulp plotted as a function of flow velocity in a $\frac{7}{8}$ in tube[29]

Comparison of the data obtained with different pipe diameters indicates that the nature of the flow at lower velocities—frictional, plug or transition—is not a function of the pipe diameter, but is a function of the bulk velocity alone.[29,46] This consideration, together with the anomalous character of the viscosity term, seems to preclude the use of any general Reynolds number correlation for pulp suspensions.

In developed turbulent flow, the friction losses for pulp suspensions are less than for water flowing at the same velocity and the effect is progressively greater with increasing concentration and with increasing flocculating tendency of the fibres. The lower energy dissipation in the suspension has been attributed to the inhibition of smaller eddies by the presence of fibres and fibre aggregates.[29] Direct measurement of the energy spectra has verified this (Fig. 7), which shows that the turbulence spectrum for suspensions is composed of lower frequencies than the corresponding spectrum for water.[30]

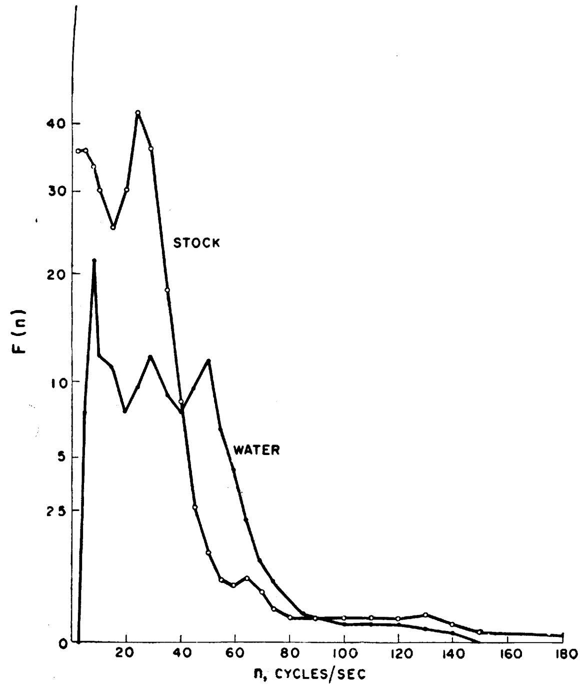

Fig. 7—The energy spectra of turbulence for water and 0.5 per cent kraft stock measured mid-way between the wall and the centre line of a 2 in pipe: ordinate is proportional to the mean square intensities per unit mass per sec at a given frequency (after Daily *et al.*[30])

The velocity profiles are blunter for stock than for water (Fig. 8) at the lower turbulent velocities, but comparisons at increasing velocities show that the two profiles approach one another as the stock profile sharpens and the water profile becomes flatter. The velocity profiles permit the calculation of the momentum transfer coefficient ϵ which is defined by —

$$\epsilon = \tau_w \left(1 - \frac{y}{R}\right) \Big/ \rho \frac{du}{dy}$$

where τ_w is the shear stress at the wall, y is the radial distance from the wall, ρ is the fluid density and du/dy is the velocity gradient at y.

At the wall, ϵ is lower for pulps than for water in conformity with the lower friction losses observed. The parabolic plot of ϵ against y, which is obtained with water, becomes hyperbolic for pulp suspensions at sufficiently high concentrations or low velocities (Fig. 9). The momentum transfer coefficient may be considered to be the sum of a turbulent momentum transfer coefficient ϵ_t and a fibre momentum coefficient ϵ_f.[47] This partition

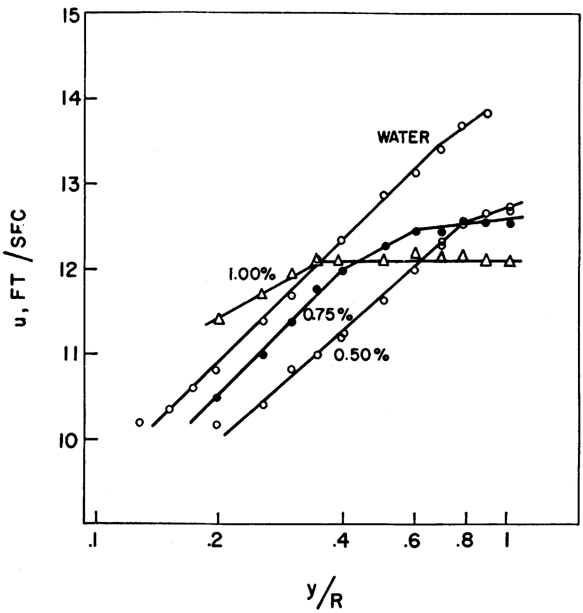

Fig. 8—Velocity profiles for water and three concentrations of kraft stock flowing at a bulk velocity of 10 ft/sec in a 2 in pipe: the plot is semi-logarithmic (after Daily *et al.*[30])

is based on the consideration that momentum is transferred both by turbulent fluid interaction and by mechanisms involving fibre interactions. The value of ϵ_f is a function of the type of fibre and the fibre concentration. It increases toward the centre line of the conduit so that ϵ_t is the dominant component of ϵ at the wall and ϵ_f is dominant near the centre. The effect of fibre properties is illustrated by groundwood, which exhibits flow behaviour intermediate between water and chemical stock as would be expected from a consideration of the relative mean fibre lengths.

It is pertinent to note here that at comparable volume concentrations (up to 1.5 per cent) more regularly shaped particles such as spheres have been found to have a minor effect on the turbulence properties as inferred from diffusion experiments.(48)

It is of interest also to compare the observations of the flow of pulp

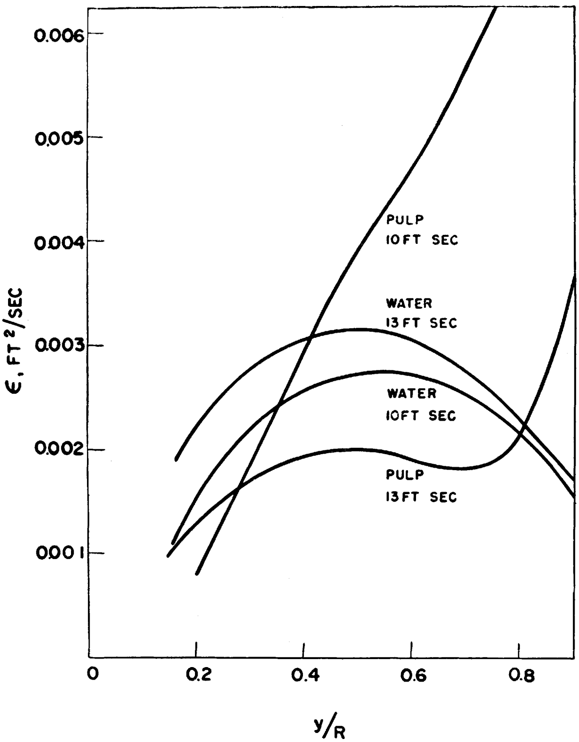

Fig. 9—Values of the momentum transfer coefficient ϵ calculated from velocity profiles for water and 0.75 per cent kraft stock flowing in a 2 in pipe at bulk velocities of 10 and 13 ft/sec (after Daily *et al.*(30))

suspensions with the studies by Shaver and Merrill(49) of the flow in pipes of a wide range of pseudoplastic polymer solutions. The latter workers conclude that, in these systems, the turbulent velocity profile is sharper than in Newtonian flow, wall-slip is negligible, no plug flow exists either in the laminar or turbulent regimes and that the flow processes can be correlated on the basis of the power law $\tau = b(du/dy)^s$, where b and s in the relation between the shear stress τ and velocity gradient du/dy are constants for a given solution over a wide range of flow conditions. All the conclusions mentioned are contrary to the observed properties of flowing pulp suspensions.

The nature of pulp flow in pipes appears to be almost unique, although there are occasional reports of slurries or solutions that have lower turbulent friction losses than the suspending medium or solvent—clay slurries,(50) napalm in gasoline,(51) thorium oxide suspension(52) and certain polymer solutions.(53) Similarly, there are reports of systems in which flow occurs by the formation of an annulus of the low viscosity component at the wall—clay suspensions and lubricating greases.(55)

It has been noted that blood represents in many ways a system analogous to fibre suspensions. Both cases involve the flow behaviour of a crowded system of flexible particles (the red cells in the case of blood) in which free rotation of the particles is prevented by particle interactions. Studies of the flow properties of blood(56) have led to the conclusion that plug flow occurs in the centre of the channel and that the required shear occurs predominantly in an annulus of plasma at the wall. Experimental data suggest the idea that at increasing flow rates turbulence develops in the plasma annulus before appreciable breakdown of the plug occurs.

Recently, investigations have been undertaken(57) to determine the behaviour of suspended deformable particles (fibres and fluid drops) flowing through a tube. Predictions of the rotation and deformation behaviour have been verified. In addition, it has been shown analytically and experimentally that in Poiseuille flow individual deformable particles are progressively displaced toward the tube axis, whereas rigid particles are not. The investigation is now being extended to more concentrated suspensions of deformable particles (blood, fibre suspensions, coarse emulsions) to determine their microrheological behaviour.

The properties of fibre suspensions, particularly phase separation, preclude the application to stock flow of the various methods proposed for the correlation of the data in terms of conduit dimensions and meaningful fluid parameters as has proved successful for other slurries and pseudoplastics.(58–60) For the same reasons, the prediction of the whole flow curve from rotational viscometer data is unlikely to be successful although several workers have suggested this approach.(44,61)

Studies of pipe flow have pointed out the error of attempting to specify the 'viscosity' of pulp suspensions of papermaking concentrations. Of course, it is apparent that the classical concept of a fluid viscosity, which is derived wholly from stress-biased molecular diffusion processes, is inapplicable to suspensions, since energy is transferred by processes other than at the molecular level. Nevertheless, a valid extension of viscosity measurement to the flow of suspensions appears to be justified when a condition approaching the laminar flow of a homogeneous suspension is attainable. Here, a total viscosity is measured, which is determined by the viscosity of the suspending medium, the local non-uniform shear conditions around the particles and particle interactions. When the particle size is appreciable in relation to the size of the viscometer, homogeneity of concentration and shear cannot be assumed and the geometry and dimensions of the viscometer affect the measurement (chiefly because of wall effects) and the coefficient measured is no longer a parameter of the fluid alone. In pulp suspensions, particularly of long-fibred pulps, wall effects are predominant and homogeneous laminar flow cannot be achieved. The plug flow at low velocities is superseded by turbulent flow as the velocity is increased. The production of rolling flocs at the wall at low velocities, the effects of wall roughness and the plugging of orifices by stock are additional evidence of behaviour that is inconsistent with the concept of a viscous fluid.

It is important to recognise that the turbulence in stock is not predicted from Reynolds numbers based on water viscosity. Although one portion of stock may be in turbulent flow near a boundary, the flow in the centre of the channel may be plug flow or large masses of pulp may move without internal shear—a condition that has been described(62) as 'boiling flow'. Pipe flow experiments(29) indicate that at papermaking consistencies stock flow at 100 ft/min relative to a boundary is required to maintain turbulence in the stock adjacent to the wall, whilst flow rates of three or four times this value are required to maintain turbulence in the whole mass of stock.

As with Newtonian liquids, a turbulence may be induced at lower velocities by flow through grids or perforated rolls or plates. Such processes are useful in mixing and dispersing stock or evening out velocity differences across the machine, but the turbulence, particularly the smaller fluctuations, may be expected to decay quite rapidly.

Head box flow

General

Qualitatively, some of the formation characteristics we find in machine-made paper may be demonstrated quite simply in the laboratory sheet-machine, where vortex motion, flow past a bluff object, flow through a grid, wave motion, air bubbles and stock sedimentation can affect the uniformity of the sheet and the orientation of fibres. The conditions mentioned often exist in the flow box. It is essential for paper uniformity that their effects are not felt during sheet formation on the wire. The requirements for sheet uniformity are that flocculation be minimised, that the bulk velocity across the machine be uniform and that cross-flows be absent. A uniform flux of fibre through the slice across its width is a necessary but insufficient condition for sheet uniformity.

The effect of the difference in speed of stock and wire on fibre orientation and properties associated with orientation is reasonably well established.[63] Fig. 10 shows the effect of stock velocity at constant wire speed on machine-direction tensile strength. The appreciable drop in strength at about

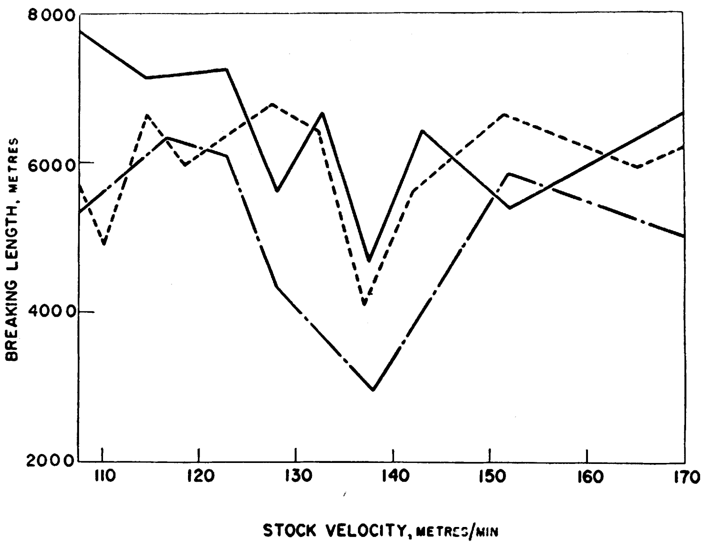

Fig. 10—The change in breaking length produced by varying the relative velocities of slice jet and wire: the wire speed is 150.2 m/min and the stock velocity is varied over the range shown in three different experiments (after Andersson and Bergström[63])

138 m/min corresponds to a minimum orientation factor and a minimum strength anisotropy. It is to be noted that the sheet properties are quite sensitive to the stock/wire differential in this critical region. If head boxes produce local velocity variations across the slice, the fibre orientation and other properties dependent on this differential will vary from point to point and represent a source of non-uniformity that may be independent of basis weight.

Using a technique to permit rapid and convenient differentiation of chemical and groundwood fibres,[64] we have recently examined a wide variety of newsprint samples and found that about half of them showed alternating regions of oriented and random chemical fibre on the wire side.

It has also been pointed out[65–67] that disturbances before the slice can contribute to the instability of the stock on the wire. Thus, uneven flow or pressure profiles in the jet can be amplified by free surface flow phenomena over the table rolls and represent a source of non-uniformity in the sheet.

It is not our intention to consider specific flow box designs, but some features common to many inlets deserve some comment. Flow to the slice usually involves a stock acceleration from a relatively low velocity to a velocity 5 or 10 per cent below the wire speed. If the approach flow conditions are such that appreciable flocculation is present, the behaviour of

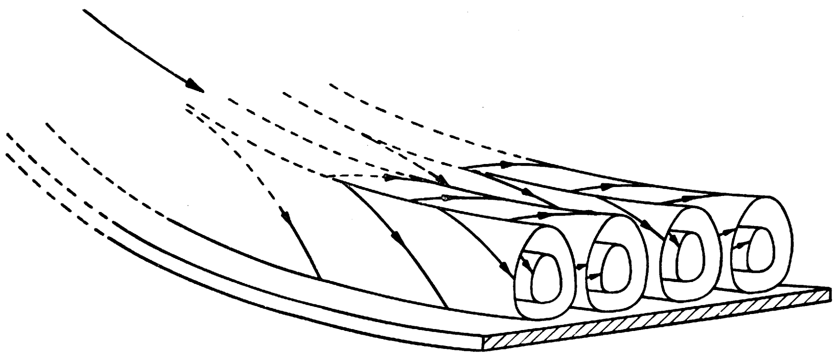

Fig. 11—Representation of the secondary flow produced by the flow of a fluid over a concave boundary (after Gortler[70])

these flocs in the converging accelerating flow is of interest. The flocs are subjected to forces tending to elongate them[68] and when the forces are sufficient the flocs fail in tension and so are broken up. Since the mechanical properties of the flocs are not uniform and the rupture process is characteristically random, passage through the slice does not ensure uniformity of fibre concentration unless sufficient mixing is provided by turbulence or other means.

In the 'frozen flow' head box, a uniform fibre network structure approaching the slice does not produce a satisfactory sheet unless a rotating stave roll or other mechanism for disrupting the structure is present.[69] Since the roll does not create appreciable turbulence, it may well be that its function is to ensure that the fibre network structure is broken down more uniformly than can be effected by simple acceleration and shear.

A second point is the common occurrence of stock flowing along a concave surface in the slice approach. The possibility exists here that conditions are favourable for development of secondary flows or instabilities of the Gortler[70] type (Fig. 11). These flows are analogous to the secondary flows in pipe bends and to the Taylor[71] vortices in Couette systems (Fig. 12).

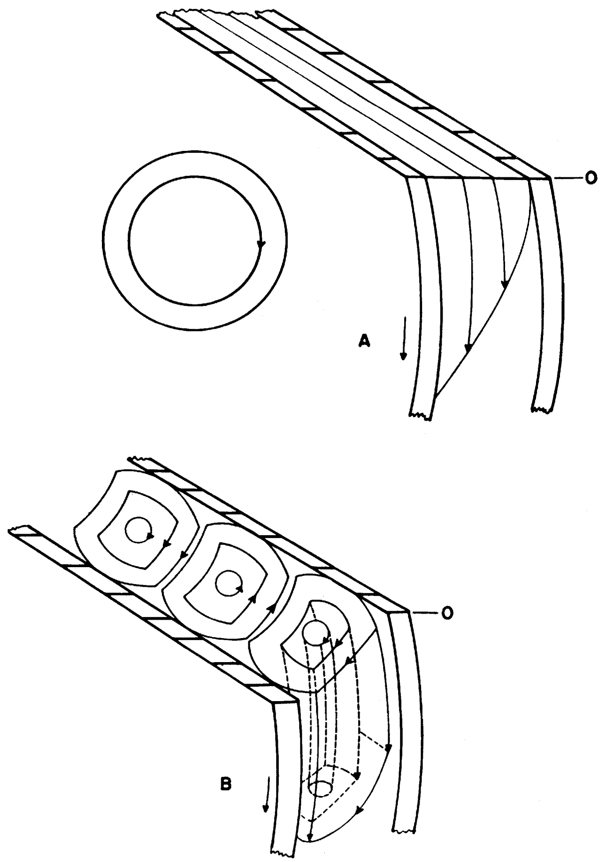

Fig. 12—Secondary flow in a concentric cylinder apparatus produced by rotating the inner cylinder (after Nissan and Haas[73])

In the extreme case discussed by Lee, flow around a roll rotating in a concentric housing immediately before the slice produced fully developed Taylor vortices, which caused a non-uniform distribution of fibre and air bubbles and so resulted in pronounced machine-direction streaks down the wire.

The non-uniform fibre distribution may result from differential sedimentation in the vortex field, wall effects or fibre flocculation phenomena. More recent studies of Taylor vortex motion have been reported.[72,73] The first considers the effect of imposing an axial flow between the cylinders to produce helical

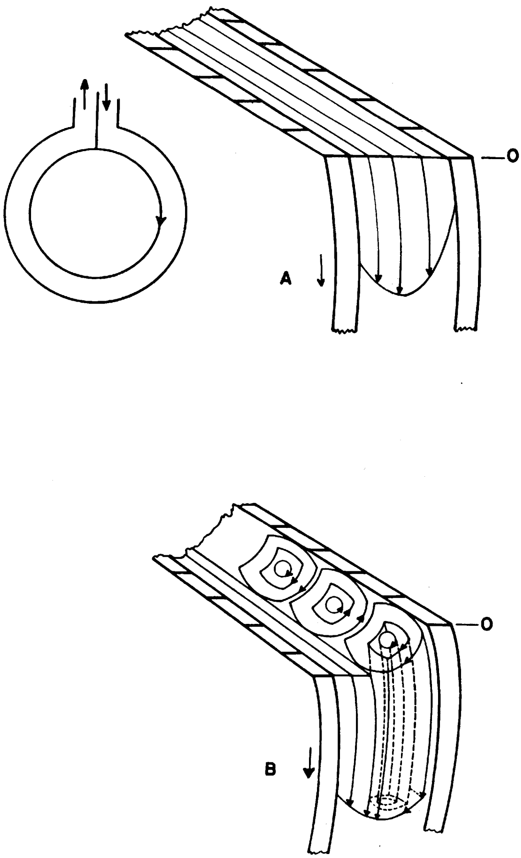

Fig. 13—Secondary flow in a concentric cylinder apparatus produced by rotating the inner cylinder with additional flow produced by pumping fluid in the same direction as the rotation (after Nissan and Haas[73])

flow patterns; the second treats the cases of liquid pumped with or opposed to the inner rotating cylinder. Pumping in the same direction as the rotor causes vortices to be formed between a layer of fluid in stable flow and a concave boundary (Fig. 13), thus demonstrating the identity of the Taylor and Gortler phenomena.

Some head box geometries are such that analogous flows can be imagined. Calculations based on typical dimensions and velocities show that Liepmann's value for Gortler's instability parameter[74] may often be exceeded, although the parameter includes a viscosity term that is indeterminate. The parameter is given by $p = R_\theta \sqrt{\theta/r}$, where R_θ is the Reynolds number based on the boundary layer momentum thickness θ and r is the radius of curvature of the concave boundary. The critical value of p is 9.0. Even though the development of stable Taylor-Gortler vortices may not occur generally, partially developed secondary flows of this type are a distinct possibility and can provide a source of heterogeneity.

The detection and prevention or control of secondary flows is considered to be of special importance. Taylor vortices provide one example; another is the vortices, stationary or shed, that are formed by flow around baffles. In this case, the vortices not only constitute a source of non-uniformity themselves, but may act as a pressure sensitive constriction to the main flow, so that appreciable velocity fluctuations may result from small pressure changes.[62] Another secondary flow that may be of consequence is the flow or circulation into corners, leading to cross-flow velocities.

The presence of fibres and aggregates has been shown to damp out small-scale turbulence in water and to increase the momentum transfer coefficient in sheared liquids. It might be expected therefore that secondary flows would be less pronounced in stock than in water under similar conditions of geometry and bulk velocity. This has in fact been shown by observations that the formation of Taylor vortices in the Couette system mentioned before is inhibited by the presence of fibres.[75] It has been shown[76] that increasing concentration of fibres decreases the equivalent length of fittings in pipelines (reducers, bends, expanders), presumably for similar reasons.

In head boxes, the stock flows through converging and diverging channels, around bends and baffles, along concave or convex surfaces, through perforated rolls and plates and through channels of various cross-sections. Prediction of flow patterns in these systems are based on hydrodynamic theory or on the observed behaviour of water in scale models or analogues. Whilst this approach is valuable, it is believed that it provides only an approximate picture of stock flow in view of the differences in hydraulic behaviour between stock and water, which have already been discussed.

Unfortunately, experiments in which the flow of stock has been compared to the flow of water in the same system have not frequently been reported, except in the studies of flow in pipes. It is significant that in the few published results—pipe flow, velocity profiles in slices,(77,78) a flow in Couette system(75)—the differences have been substantial.

Experimental methods

The investigation of head box flow and its effects has proceeded using both empirical and fairly scientific approaches. The use of formation testing and basis weight analysis can be used as tools to characterise or assess head box flow on existing machines. The formation tester may be used to assess

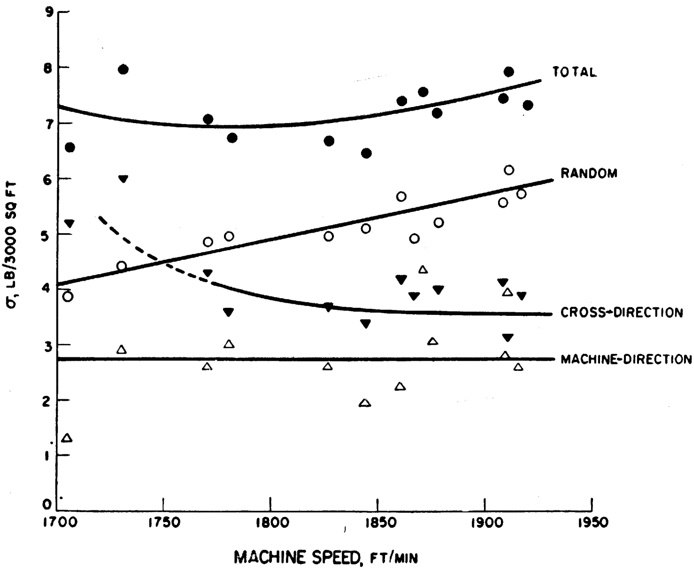

Fig. 14—Analysis of total basis weight variance into random, machine-direction and cross-direction components over a range of machine speeds: the random component increases with speed while the cross-direction component decreases somewhat and the machine-direction component shows no systematic variation (after Burkhard and Wrist(4))

the effects of deflocculants, de-aeration, head box consistency and other stock properties. It has been noted that, when no stock changes are made, the coarse formation may vary considerably across the machine or with time, while the finer structure is rather constant.(18) This suggests that the fine grain of the paper is attributable to stock properties, whereas the coarser formation is primarily a function of machine and operating variables. The basis weight variation is even more a function of the machine rather than the stock and the results of basis weight analysis that have been reported are mainly specific to the particular machine investigated and relate to slice openings, surges, vibrations, etc. The random component in basis weight evaluation, however,

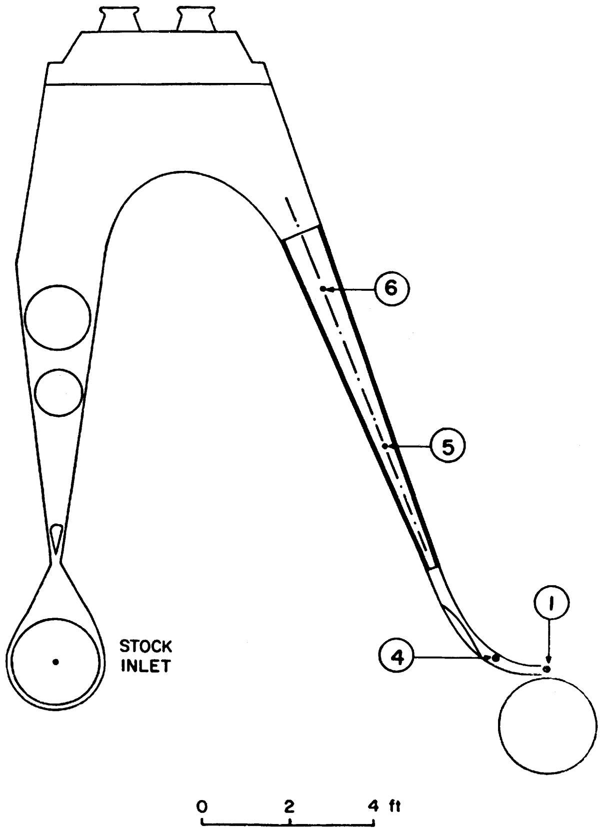

Fig. 15—Cross-sectional view of the head box in which flow was investigated by tagged fibre additions: points of addition are indicated by numbers[80]

appears to be of more general interest, being presumed to have its origin in the large-scale turbulence in the stock. It has been found to increase with speed on a given machine (Fig. 14) and has been suggested as a basis for comparing the hydrodynamic design and performance of different head boxes.[4,5,27]

Gavelin[27] has recently reported a fairly comprehensive approach to assessing machine performance. The beta-gauge profile analysis has been used to separate the machine, cross and random variance components. This technique is supplemented by high-speed photography of the table, slice profile measurement and vibration analysis in the region of the head box to discover and trace the origins of periodic variations in the sheet.

Another method of considerable potential, which uses analysis of the finished sheet to investigate head box flow, is based on the introduction of

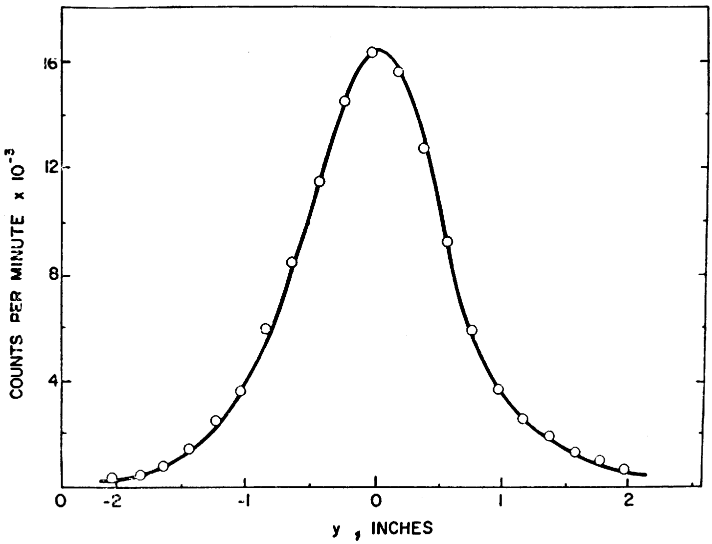

Fig. 16—Distribution of activity in paper due to addition of tagged fibres over the slice: the curve is nearly Gaussian as would be expected from turbulent diffusion theory[80]

tracer fibres at various points in the head box and determining the distribution of the added fibres in the finished sheet.

Sergeant[24] has described an experiment based on this technique. Dyed fibres were added over the slice to determine the lateral dispersion of the stock on the wire and similar additions were made at each of the screens feeding the head box to determine the efficiency of mixing in the inlet system. Quantitative results were obtained by making fibre counts.

The method was extended and improved by the use of radioactively tagged fibres. This permitted the assessment of the final fibre distribution by semi-automatic means and the use of autoradiography permitted the visualisation of the tagged fibre distribution and orientation. In addition, all tagged fibres in the sheet are counted rather than the surface fibres alone.

Two types of experiment have been described. In one,[79] the efficiency of mixing following the screens was investigated. In the second and more

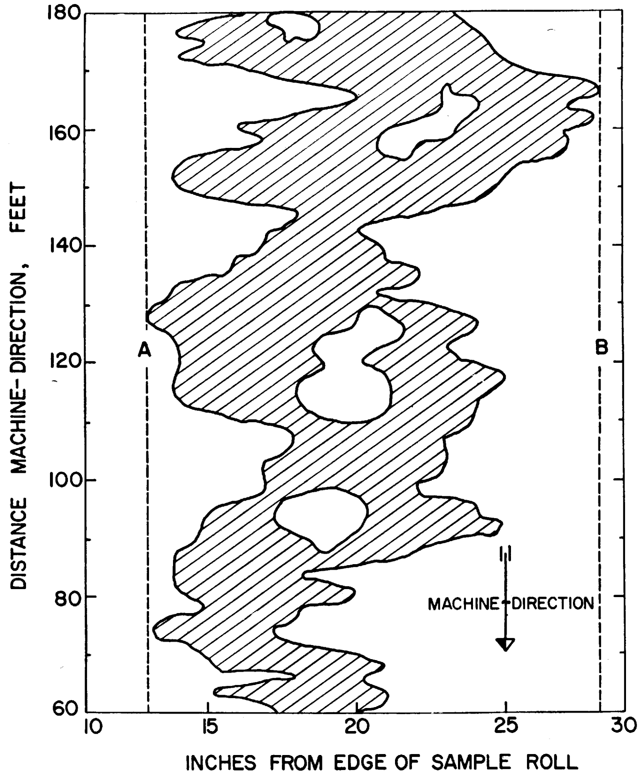

Fig. 17—Outline of activity pattern in paper due to addition of tagged fibres in the head box at position 6 (Fig. 15): the location of rectifier plates is indicated by the dotted lines at *A* and *B*[80]

elaborate experiment,[80] additions of fibres were made over the slice and at several points in the approach system of two newsprint machines, one of which is shown in Fig. 15. Each addition of fibres produced a streak of active fibres in the paper that varied in width as a result of small-scale turbulent diffusion processes (Fig. 16). The streak varied also in position across the machine, reflecting large-scale lateral disturbances (Fig. 17). Thus, it is possible to evalute large-scale and small-scale disturbances almost independently.

Consideration of the differences in the distribution of activity corresponding to additions made at different distances from the slice permits conclusions to be drawn about the nature of the flow between successive

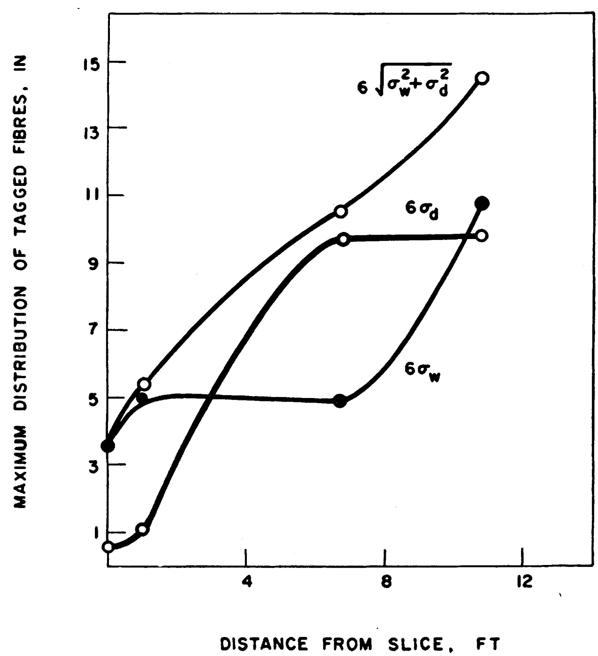

Fig. 18—The distribution of activity produced in paper by addition of tagged fibres at points 1, 4, 5 and 6 (Fig. 15 and Table 3): the total spread of activity is analysed to show diffusion by small-scale and large-scale processes, respectively

points. The results for four of the points of addition are shown graphically in Fig. 18. Numerical data are given in Table 3.

As anticipated, the maximum distribution of fibres is broader as additions are made farther from the slice. It is evident in the data that the large lateral disturbances that exist in the body of the head box and are revealed in the distributions obtained for additions 5 and 6 are largely damped out in the converging inlet and produce little effect on the wire. It is seen

TABLE 3—DISTRIBUTION OF TAGGED FIBRES[80]

Addition point[(a)]	*Distance to slice, ft*	*Streak width, in*		*Streak displacement, in*		*Total range, in*
		σ_w	*Max.* (6 σ_w)	σ_d	*Max.* (6 σ_d)	$6\sqrt{\sigma_w^2 + \sigma_d^2}$
1	0	0.58	3.48	0.09	0.54	3.52
4	1	0.88	5.28	0.17	1.02	5.38
5	6.75	0.81	4.86	1.63	9.78	10.92
6	10.75	1.80	10.80	1.64	9.84	14.64

(a) See Fig. 15

Terms σ_w and σ_d are the standard deviations of the activity from its mid-point and displacement of the mid-point of activity from its mean position, respectively

also that small-scale turbulence is present between positions 6 and 5, but is absent until further turbulence is generated near the slice, presumably by the flow evener plates and rods. The identical lateral displacement observed for positions 5 and 6 is explained by rectifier plates with a spacing of 15.5 in, which limit lateral movement of the stock.

More detailed analysis of the data can provide further information about detention times, turbulence generation and decay and location and size of large-scale eddies. In addition information about flow on the wire is available and 'snaking', turbulence, relative motion of top and wire side stock and fibre orientation can be evaluated. The technique thus offers a method for investigating many of the wet end factors affecting uniformity, the detailed information obtainable being limited only by the design of the equipment and the extent and precision of the analysis.

The flow in the head box has been investigated by other means. The use of scale models has frequently proved helpful,[24,81–83] particularly when fabricated from transparent material and when flow patterns are visualised by the introduction of dye or particles. The limitation has been pointed out[82] that, for strict dynamic similarity between the model and machine, both the Reynolds number Ud_1/ν and the Froude number $U/\sqrt{gd_2}$ (where U is velocity, ν is the kinematic viscosity, g the gravitational constant and d_1, d_2 are appropriate dimensions) must correspond in the general case that a free surface is present. This is not generally possible, since the characteristic length appears in the denominator of the Froude number and the numerator of the Reynolds number. This consideration, together with the indeterminate nature of the viscosity parameter for stock and the length parameter for the slice opening,[83] reduces the significance of scale-model studies to an uncertain approximation.

On existing head boxes, pressure or velocity sensitive probes have been used to map the flow patterns,[78,83,84] to measure friction loss in the slice[83] and to assess the turbulence.[84] Voith[85] uses a quarter-scale head box for development purposes, which has facilities for making pressure and velocity measurements at 150 points between the distributor inlet and the slice. Uniformity of flow across the machine has been assessed volumetrically by collecting the flow from unit widths across the slice.[83] In most cases, the problem of the stock hanging up on probes inserted into a flowing suspension has restricted their use to the investigation of water flow.

Concluding remarks

Saleable paper is being produced on Fourdrinier machines operating in the range of 2 000 ft/min, but the machine designer and the papermaker face serious problems relating to production and quality at these and lower speeds, which stem from a lack of basic knowledge of the relevant hydrodynamic phenomena. This lack of knowledge may well be preventing significant advances in papermaking.

This ignorance relates first of all to the fluid mechanical properties of the stock itself, which vary with the type of stock and basically with the fibre properties. Some knowledge of the equilibrium flow properties of stock in circular pipes has been accumulated, but how does stock behave in a system in which the velocity of flow and the geometry of the channel are changing? The kinetics of flocculation and deflocculation, of growth and decay of turbulence are not known.

Head boxes have a complex geometry and an adequate description of the flow would not be simple, even if the stock could be regarded as a simple fluid. Entry conditions; stability, growth and separation of boundary layers; generation and decay of secondary flows of many kinds; intensity, scale and distribution of turbulence—these are all of importance in view of the exacting requirements that must be met for the production of a uniform, stable slice discharge. A great amount of pertinent information is available in the general fluid mechanics literature, but it is likely that basic hydrodynamic studies will have to be undertaken to understand phenomena of particular interest—wide, flat jets; flow through and after distributor rolls; accelerating flow in curved channels and so on.

Interest in these problems has been growing and techniques and methods for their solution are being developed. The use of the wind tunnel for studies of rectifier roll action[86] and the use of electrical analogues[87] to determine flow patterns in the slice approach show the range of techniques that are being explored. The apparent success of the impact tube used in pipeline studies[30] and other flow sensing devices[8,83] offers the hope that probes of sufficient sensitivity and response may be generally used to determine flow patterns and measure turbulence parameters in stock. It is believed that tracer experiments of the type described above provide a simple and valuable approach to the study of head box flow.

Appendix

Mass variation in an ideal sheet

CONSIDER an area of 200 cm^2 divided into $2 \times 10^4/l^2$ squares having a side of l mm and a sample of straight fibres of uniform length λ such that the total length is 2×10^7 mm/g and the number of fibres is $2 \times 10^7/\lambda$ per g. If the fibres are allowed to fall randomly on the area, each fibre will, on the average, fall to lie in k squares,[88] where —

$$k = 4\lambda/\pi l + 1$$

Each fibre may be considered to be divided into segments by the boundaries of the elementary areas and, on the average, a fibre is divided into k segments, of which $(k - 2)$ segments are chords and 2 segments are ends.

The coefficient of variation of mass per unit area may be derived from the coefficient of variation of the number of segments per unit area and the coefficient of variation of the segment lengths.

The distribution of chord lengths was determined empirically based on the assumption of a uniform distribution of orientation and intersection of fibres with the area boundary. The distribution of fibre ends was determined by assuming an isotropic orientation of fibres and a uniform distribution of fibre centres over the whole area.

The results differ somewhat from theoretical predictions[88] as shown in Table 4, where the results for $l = 1$ and $\lambda = 3$ are listed. It is to be noted in support of the empirical data that they satisfy the requirement that —

$$(k - 2)\,\bar{\lambda}_{ch} + 2\,\bar{\lambda}_{e} = \lambda$$

whereas the predicted data do not.

The coefficient of variation (v) of mass per unit area is calculated from

$$v = 100\left[\frac{1}{N} + \frac{1}{N}\left(\frac{\sigma\bar{k}}{\lambda}\right)^2\right]^{1/2}$$

where $N = Wl^2\bar{k} \times 10^3/\lambda$ is the mean number of segments per unit area (l^2) and W is the sheet weight in grams and σ is the standard deviation of segment lengths.

If $l = 1$, $\lambda = 3$, $W = 1$; then $\sigma = 0.356$ (Table 4), $k = 4.82$ and $v = 2.88$ per cent.

If it is assumed that the standard deviation of segment length from the mean is 0.356 l over a range of l and λ values, the coefficient of variation of mass can be estimated for various 'scanning spot' sizes (l), sheet weights (W) and fibre lengths (λ) (Fig. 4).

TABLE 4—STATISTICS OF RANDOMLY FORMED SHEETS

Factor	*Predicted,*[88] *mm*	*Observed, mm*
Mean chord length λ_{ch}	0.786	0.709
Standard deviation σ	0.356	0.368
Mean end length $\bar{\lambda}_e$	0.475	0.492
Standard deviation σ	—	0.298
Mean segment length $\bar{\lambda}_s$	0.622	0.622
Standard deviation σ	—	0.356

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Transcription of Discussion

DISCUSSION

MR. G. JACQUELIN: I should like to comment briefly on the paper we published three months ago and to which Robertson referred.[1]

Among factors affecting the flocculation of pulp suspensions, we have considered more specifically the action of additives. A particular case is the action of electrolytes, on which there have been relatively few publications. I was very surprised and happy to note that, in spite of the complexity of the problem, differences between techniques and experimental conditions, we agree pretty well with several conclusions of an interesting paper published recently by Andersson,[2] especially upon the action of pH conditions, as follows—

1. pH value may affect flocculation, but in a way that depends on the ions present and on their concentrations. Polyvalent cations seem to be particularly active.

2. For the same suspension, even in a region of turbulent flow, flocculation is generally higher for low pH values and lower for high pH values. In between, a maximum or a minimum may exist depending on the mineral composition of the suspension.

3. The most significant action of electrolytes occurs when there is formation or dissolution of colloidal precipitates (calcium carbonate, aluminium hydroxyde, for instance). As colloidal particles, the fines play an important role, too.

Other points are discussed in the paper such as the action of polymers and vegetable gums, as well as the influence of temperature of flocculation and I refer those interested to the paper itself.

In conclusion, I think it is useful to keep in mind that flocculation problems are not merely mechanical and hydrodynamic problems, but that the physico-chemical aspect of the properties of the fibre surface and of the colloids in the suspension have an important role in the ability of fibres to become entangled, also in the behaviour of flocs in flowing suspensions.

DR. O. ANDERSSON: Fig. 6 shows a relationship between flocculation and rate of flow and, in the turbulent region, you have found a decrease in flocculation as the rate of flow increases. I have made similar measurements

[1] *ATIP Bull.*, 1961, (4), 287–303
[2] Andersson, O. and Brunsvick, J. J., *Svensk Papperstidn.*, 1961, **64** (13), 493–499

on 1 g/litre suspensions of bleached spruce sulphite pulp, beaten to 50° S.R., but the change in flocculation in the turbulent region is very small, if it exists at all. My experiments suggest that the flocculation does not change at all in the turbulent region. I wonder whether you could offer an explanation of this. I want to point out an important difference between your experiments and mine, namely, that my measurements were carried out on photographic plates, which were subject to circular scanning, whereas yours were taken directly from the flowing suspension, using the motion of the suspension for scanning.

DR. A. A. ROBERTSON: Perhaps your own explanation has some validity and the differences in concentration may be important too. We are using 6 g/litre suspensions of a similar stock, but unbeaten. I expect as you do, that the velocity could be reached when the flocculation curve becomes flat. If curves were carried to 1 000 cm/sec, they would flatten out. Perhaps the flocculation effect could be correlated with the pressure loss data and it might be found that a maximum deflocculation is obtained when the friction losses for stock and water become nearly equal, beyond point *E* in Fig. 1 of the Cambridge symposium paper.(28) Earlier work(34) has shown, in fact, that the flocculation curves are flat for the more dilute suspensions in turbulent flow.

A DELEGATE: Once the flocs are broken down, it seems that the measurements always give the same answer.

DR. ROBERTSON: We are satisfied from our own work that, in the turbulent flow region and even in the latter parts of the transition region, a dynamic flocculation-deflocculation equilibrium exists, because the curve in Fig. 6 can be approached from two directions. That is to say, by very violent stirring in the head box at the entrance to the pipe, one can create a better dispersion than the equilibrium dispersion in the pipe or, by slowing down the stirring, one can introduce a rather flocculated suspension. Independent of the nature of the entry conditions, the curve is reproduced.

PROF. J. D'A. CLARK: Dried unbeaten pulp suspensions give very little flocculation. Immediately beating commences, flocculation of the resulting diluted fibres increases very markedly until the fibres are sufficiently shortened. The secret is its rapid initial fibrillation. That is a most important point, so when talking about unbeaten fibres, I would ask how unbeaten are they?—since the primary wall may or may not be present.

DR. ROBERTSON: The stock I was using was a commercial pulp dispersed from the dry condition, so initial fibrillation was presumably at a minimum. I do not know the history of the pulp, but we have run the same pulp in an apparatus for nearly a month and the characteristics of the curve changed very little during that time because of any beating action that the centrifugal pump may have given.

DR. J. A. VAN DEN AKKER: Perhaps the difference between the results obtained in the two laboratories is to be found in differences in the distance between the inlet to the duct and the point of observation.

DR. ROBERTSON: Fig. 14 of one of our earlier papers[29] has some relevance here.

THE CHAIRMAN: Dr. Andersson, do you wish to comment on this question of position?

DR. ANDERSSON: I measured the turbulence at the same time and, after that region, I could just as well make it a co-ordinate showing a root mean square fluctuation.

PROF. B. STEENBERG: Do we really have to look for the mental differences? After all, it may be that your scanning rate was provided by the rate of flow, changed while the scanning rate in the Attwood and Andersson case was independent of the rate of flow. Before that point is studied, we need not look for any more complicated explanations.

DR. ROBERTSON: If Steenberg is suggesting a lack of adequate frequency response of our instruments, this has been checked and it was flat over the frequency spectrum present.

PROF. STEENBERG (*written comment*): I do not dispute your frequency response. The scanning rate in the Attwood and Andersson case is constant; but, in the Robertson case, there is a complicated distribution of scanning rates provided by the motion of the fibres in the turbulent system. In the first case, scanning rate is an independent variable; in the latter case, it is dependent on the properties of the flowing system.

DR. N. K. BRIDGE: The origin of the 2 in streaks seen in the papers from many different machines and repeated in your paper is very interesting. Have you any explanation for them yet?

DR. ROBERTSON: We included mention of it in the manuscript in the hope that somebody else would explain this phenomenon.

DR. BRIDGE: Could they be caused by a hydrodynamic condition due to the width of the slice being very much the same on all machines?

DR. ROBERTSON: No, I would hestitate to say that. We have had several levels of comment in this symposium, starting off with quantitative relations and semi-quantitative relations, qualitative relations and semi-qualitative relations. Jayme has introduced the 'detection of trends' as being at a slightly lower level than this. In order to comment on this particular question, we would have to recognise lower levels still. I suggest that some of these levels have been occupied already. They might be called informed prejudice, semi-informed prejudice and ignorant prejudice. Any comment from me would be in the lowest order; however, I think that some studies of the stability of wide, flat jets are warranted.

DR. G. BURKHARD: Recently, some new evidence of the cause of these streaks came to our attention. I am now referring to machine A–1 in Table 2 of the paper, on which very dominant streaks have developed from time to time. It is observed that on regrinding the couch the formation of streaks disappeared for some time. Furthermore, by lifting the presser roll, the recurrence of the streaks was delayed. When streaks appeared, the wire showed a distinct streaky wear pattern corresponding to the spacing of the streaks in the paper. Since nothing else seemed to correspond to the streak spacing, attention was then focused on the couch and it was found that the couch drilling pattern—or better the couch drilling pitch—corresponded very well. In examining the couch, it was found that, at every fourth hole in the axial direction, the land between holes was slightly wider than between the other holes. This is due to backlash in the couch drilling.

It is thought that this slightly wider land at a drill spacing of $2\frac{1}{4}$ in (on that couch) could well cause a non-uniform wear on the wire, owing to uneven slip and load distribution. The observations made on that machine seem to sustain this theory.

DR. ROBERTSON: Suspicion has been cast on almost everything else, but the couch roll pattern has never been mentioned as suspect before.

MR. T. ULMANEN: Do you not think that differences in the degree of swelling of different fibres have an influence on the shape and the location differences of the similar curves as given in Fig. 5?

Very often, we speak only of the purely mechanical characteristics of a fibre—such as the length, the ratio between wall thickness and the diameter of the fibre—being very important. Very seldom, however, do we mention the degree of swelling of a fibre as an important variable when investigating those rheological phenomena in which the interaction between fibres plays a considerable role.

I thought that differences in the degree of swelling of used fibres might partly explain the discrepancies between the curves worked out at the two laboratories.

DR. ROBERTSON (*written comment*): We recognise the importance of fibre swelling in its effect on the mechanical properties of fibres and in the calculation of volume concentration of suspensions, but we have not yet been able to demonstrate its explicit influence in pipe flow.

DR. ANDERSSON: A report of our recent findings is to be published later on. We have an apparatus designed by one of my colleagues for determining the stress/strain curves of pulp suspensions. In these, the strain is very small and it looks just like the stress/strain curve of paper.

DR. VAN DEN AKKER: May I speak further about the difference between the results of Robertson and Andersson? It has ofter been pointed out that turbulence does at least two things in a fibre suspension—it tends to bring fibres together, thus creating flocs and it tends also to pull them apart or disperse them. These two effects exist simultaneously. If one thinks of the two actions in terms of curves, what one observes is the sum of two curves, one going up, the other going down; possibly all that is happening here is that in Andersson's laboratory one effect is just enough stronger than the other that an essentially horizontal line is obtained, whereas in Robertson's laboratory conditions are different and the relative importances of the two effects are such that a sloping line is obtained.

MR. D. ATTWOOD: We have experimental evidence in support of Andersson's results and we too would expect a straight line for fully developed turbulence. We are obtaining our results in a similar way, by photographing the tube.

DR. S. G. MASON: When this work was well on, we thought that the properties of pulp fibres suspension were unique. It has recently been brought very forcibly to our attention that the flow properties of human blood in the veins and arteries have a very close relationship to those of pulp suspensions as described by Robertson. The connecting link between the two systems is that, in pulp suspensions, we are dealing basically with flexible prolate-spheroidal (thread-like) particles and, in human blood, we have a suspension of flexible oblate-spheroidal (disc-like) particles. It so happens that the mathematics of the two particle systems are identical.