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THE FLOCCULATION OF PULP FIBRES

R. J. Kerekes, R. M. Soszynski and P. A. Tam Doo
The Pulp and Paper Research Institute of Canada and The Department of Chemical Engineering, University of British Columbia, Vancouver, B.C., Canada, V6T 1W5

ABSTRACT

This paper reviews current knowledge of pulp flocculation over the entire range of consistency found in pulping and papermaking, from dilute suspensions of fibres in water to dry fibres suspended in air. Some of the key factors that govern flocculation in low consistency aqueous suspensions are shown to apply with changing emphasis over the entire consistency range. Several recent findings from our laboratory that fill gaps in current knowledge are also reported.

1. INTRODUCTION

Pulp fibres are stored, transported, and processed in fluids throughout the unit operations of pulp and paper manufacture. Water is the most common suspending medium, but other fluids may also serve this purpose. For example, air is the vehicle in dry forming, and steam is the carrier in the discharge line of a TMP refiner. Whether suspended in a gas or liquid, pulp fibres flocculate in all flowing suspensions of practical interest in pulping and papermaking.

Pulp fibres form networks, which are defined here as interconnected systems in which each fibre is in contact with other fibres. Various types of cohesive forces may exist at fibre contact points. These impart mechanical strength to the network in proportion to their magnitude and the average number of contacts per fibre. The networks are thereby self-supporting structures having solid-like behaviour. When the fibrous network is caused to flow, these strength-related properties give the fibre suspension unique rheological properties.

However fibre networks are never uniform. The fibres within them are always distributed unevenly, giving local mass concentrations called flocs. Because they have a higher mass density than the network average, flocs have more contact points and therefore higher strength than the network average. In flowing systems, they may rupture from the network and thereupon act as independent bodies. Such flocs are called coherent flocs in this paper. The term flocculation is generally used to describe both the state of uneveness of fibre networks as well as the process by which all fibre networks form.

Our current understanding of fibre flocculation and the flow properties of pulp suspensions is derived from a considerable body of research conducted over the past thirty years. The major findings from these studies have been summarized in various reviews, such as that of Parker (1), and papers presented at earlier symposia of this series, notably those of Forgacs, Robertson and Mason (2); Steenberg, Thalen, and Wahren (3); and Norman, Moller, Ek, and Duffy (4). More recently, Wahren (5) has reviewed current understanding of fibre network structures and Kerekes (6) has reviewed fibre flocculation in decaying turbulence.

As these review papers show, past studies of fibre flocculation have concentrated upon low consistency pulp suspensions, most often in the range 0-1.5% commonly found in paper machine headboxes. Indeed, the objective of most past studies has been to improve understanding of the papermaking process. However, interest in pulp flocculation at high consistency is growing. New developments in screening, pumping, and dry forming aim to achieve at high consistency what was once thought possible only at low consistency. The objective of this paper is to review pulp flocculation over the entire range of consistency found in pulping and papermaking, using where possible findings from the oft studied case of low consistency suspensions to expand our understanding of flocculation in the higher consistency ranges.

To facilitate the discussion, we first delineate some convenient ranges of pulp consistency. This variable, C_m, is defined as mass of fibres divided by mass of fibres and water. No account is taken of the amount of air present. Consistency is one of the most important factors affecting pulp flocculation and also one of the most commonly measured. Recognizing that any choice of consistency ranges is arbitrary, we have chosen ours to coincide with those found in the major unit operations of pulp and paper manufacture.

Low Consistency (0-8%)

The low consistency (LC) range we define here encompasses fibre suspensions up to the consistency at which significant amounts of air appear in the suspension. The upper limit of 8% is the approximate consistency at the dry line on a paper machine. Above it, the fibre suspension on a paper machine is properly called a wet web.

Within the LC range are several sub-ranges. The first of these is a "dilute" sub-range, 0-1%. This is the consistency range used in headboxes of conventional paper machines. Another sub-range, 1.5-5%, is referred to as "high consistency" in some new methods of screening and forming. Another sub-range, 3-5%, covers the consistencies at which pulp suspensions are commonly pumped and stored. A consistency of 5-6% is generally considered to be the upper limit at which pulp suspensions can be pumped by conventional centrifugal pumps.

Medium Consistency (8-20%)

The medium consistency (MC) range is attained by dewatering pulp suspensions under a vacuum and then dispersing the resulting mat by mechanical means. The upper limit, 20%, is attainable by the high vacuums commonly found on the couch rolls of a paper machine. The lower values, 8-15% are produced by the vacuums found in deckers and washers. Pulp is commonly stored, pumped, and washed in this range.

High Consistency (20-40%)

The high consistency (HC) range is attained by pressing water from pulp and then dispersing the resulting pad mechanically. Pulp is sometimes bleached in this consistency range, for example in oxygen bleaching. This is also the range at which mechanical pulp discharges from chip refiners.

Ultra-High Consistency (40-90%)

The ultra-high consistency (UHC) range is attained by evaporating water from pulp and dispersing the pulp by mechanical means. As the consistency increases through this range, hydrogen bonding between fibres becomes increasingly significant. Flash drying is a typical unit operation carried out in this range.

"Dry" Consistency (90-100%)

This is the range of dried pulp. Individual dry fibres are produced by mechanical defibration of dry pulp mats or aggregates. Pulp is transported and formed into paper products in this consistency range in dry forming.

2. FLOCCULATION AT LOW CONSISTENCY (0-8%)

Most of our understanding of pulp flocculation has been gained from studies in the LC range. Therefore this range will be discussed extensively here.

2.1 Contact Between Fibres

At consistencies below 0.1%, the majority of fibres in a pulp suspension are not in continuous contact. To form local network structures (flocs), fibres must collide and then remain in contact. Collisions occur when fibres are present in sufficient number and have a relative velocity between them. Because of their large length to diameter ratio, fibres collide in rotation as well as translation, and thereby form flocs by mechanical entanglement (7,8,9). Recognizing this, Mason (8,10) defined a "critical concentration" at which fibres are likely to collide in rotation. This concentration represents the condition at which only one fibre exists in the volume swept out by a single fibre. From simple geometry, Mason showed that the critical concentration is given by

$$C_v\, r^2 = 1.5 \tag{1}$$

where C_v is the volumetric concentration of fibres and r is their length to diameter ratio.

The concept of a critical concentration has proven to be a useful one over the years. Although the volume swept out by flexible fibres is less than that given by equ. ion (1), the underlying notion of Mason's concept -- that fibre crowding in rotation is a key factor in determining flocculation -- is a useful one at any concentration. It is so because collisions from rotation in any fibre suspension are likely to lead to inter-fibre contact and thereby flocculation. Thus Mason's concept may be extended to the more general case in which any number of fibres may exist in the swept volume of a single fibre. Equation (2) below gives a quantitative relationship between this number of fibres, n_f, and C_v and r

$$n_f = \frac{2}{3} C_v r^2 \tag{2}$$

It is apparent that equation (1) is a special case of equation (2) when $n_f = 1$.

The variable n_f is a measure of fibre crowding in rotation and thus the level of interfibre contact to be expected in a flowing suspension of fibres at any concentration. It is also an indicator of the level of interfibre contact in a network formed from a flowing suspension. For the case of a randomly-distributed network of fibres, Meyer and Wahren (5) derived a theoretical prediction of the number of contacts per fibre, n_c, from an analysis of network structures. Based on statistical considerations, they obtained the expression

$$C_v = \frac{16 \pi r}{\left[\dfrac{2r}{n_c} + \dfrac{n_c}{n_c - 1}\right]^3 (n_c - 1)} \tag{3}$$

for the case in which all fibres are of equal length and diameter and all are active members of the network. In pulp suspensions where $n_c \gg 1$ and $r \gg n_c$, equation (3) may be simplified and combined with equation (2) to give the approximate relationship

$$n_f \simeq 4n_c^2 \tag{4}$$

Thus, n_f is directly related to n_c for randomly distributed fibre networks under the conditions stated above. In other cases, its relationship to n_c is unknown, but clearly n_f is an approximate indicator of the level of inter-fibre contact in any fibre suspension or network. It will be used as such in this paper.

2.2 Forces at Fibre Contact Points

The mechanical strength of fibre networks is derived from cohesive forces at fibre contact points that oppose relative movement between fibres. These forces may be of four types. For convenience, we have labelled them Types A, B, C and D, in this paper.

Type A - Colloidal: These are the well-known electrostatic and electrokinetic forces which exist between small particles. Their strength depends on intimacy of contact, which is difficult to achieve between the rough surfaces of fibres, and on chemical additives that modify the negative charge found on fibre surfaces.

Type B - Mechanical Surface Linkage: This is a hooking force caused by mechanical entanglement of fibres having kinked or curled configurations, or fibrillated surfaces. When a force is applied to separate fibres, the reaction force caused by hooking at contact points opposes relative movement between them. This type of cohesion depends on surface fibrillation, the degree to which fibres are contorted, and fibre stiffness. It is illustrated in Figure 1.

Type C - Elastic Fibre Bending: Here the cohesive force between fibres is caused by frictional resistance induced by normal forces at fibre contact points. This type of force is also illustrated in Figure 1. The normal forces arise when elastically bent fibres are restrained from straightening as a result of contact with other fibres The ultimate source of this cohesive force is therefore an internal stress within individual fibres rather than an externally imposed stress on the network.

Type D - Surface Tension: Bubbles of undissolved gas (usually air) at fibre interstices produce cohesive forces as a result of surface tension.

Prior to 1950, Type A forces were believed to be the principal factor in the flocculation of pulp suspensions. Flocculation was therefore treated as a problem in colloid chemistry.

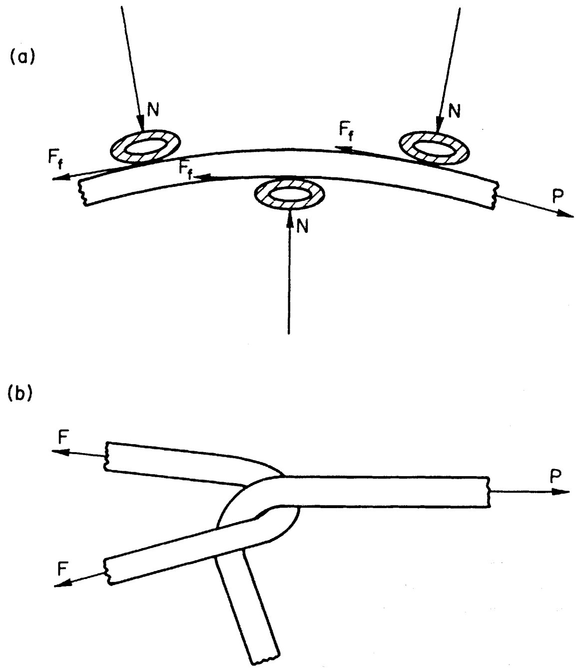


Fig 1—(a) Type C cohesion is caused by a surface friction force resulting from normal forces imposed by fibre bending; (b) Type B cohesion is caused by hooking of whole fibres, or if the fibre is very fibrillated, by the hooking of fibrils protruding from fibre surfaces.

The findings of Mason and co-workers, some of which were reported at the earliest symposia of this series (10), showed that mechanical entanglement was a far more important factor in fibre flocculation than was Type A cohesion, even at concentrations just slightly above the critical concentration. Mason's findings shifted the focus of subsequent research on fibre flocculation from colloid chemistry to hydrodynamic behaviour of pulp suspensions and the properties of fibre networks.

Later research, particularly that of Wahren and co-workers, increased our understanding of fibre networks. Specifically, Meyer and Wahren (11) identified Type C cohesion and how it forms. Fibres, bent by hydrodynamic forces during agitation, lock into a network in a bent configuration after the agitation ceases when individual fibres are restrained from unbending by at least three alternately opposed points of contact (3,11). The normal forces caused by elastic fibre bending produce frictional forces which inhibit movement between fibres. Fibres in this constrained position are "active" members of the network whereas unconstrained fibres are "passive" members (3). Meyer and Wahren suggested that networks with C cohesion first appeared at the sediment concentration (the concentration at which sediment is formed from the settling of fibres from a dilute pulp suspension) (12,13). Accordingly, Type C cohesion is strongly dependent upon the number of contacts per fibre (n_c), fibre flexibility, and the coefficient of friction between fibres. It is also strongly linked to a decay and cessation of shear (3).

The dominant picture of fibre flocculation presented in the literature of recent years is that produced by Type C cohesion. However, as shown in Figure 2, Types A,B and C cohesive forces may all be present in the LC range $0.3\% < C_m < 5\%$. Type D forces may also exist when there is substantial air present in the suspension, although this is not normally the case. Where Types A,B and C forces all exist, Type C is usually dominant, but Types A and B may also contribute significantly to network strength. For example, if the fibres in a pulp suspension are highly contorted and stiff, Type B forces may be larger than Type C ones; if strong flocculants are present, Type A forces may also be significant. As consistency decreases, the relative importance of Type C forces decreases with respect to Types A and B because there are fewer contacts, and lower forces at each contact point owing to less fibre bending. Below $C_m \simeq 0.3\%$, Type C forces may cease to exist altogether.

In papermaking, flocs produced by mechanical entanglement, (Types B and C) are generally associated with paper "formation" -- the uniformity of a paper sheet visible to the naked eye in transmitted light. On the other hand, Type A cohesion is generally linked to "retention" -- the adhesion of fines and fillers on fibre surfaces. The latter is also termed "flocculation", but is considered "micro-flocculation" as opposed to "macro-flocculation" of long fibres in a pulp suspension (14).

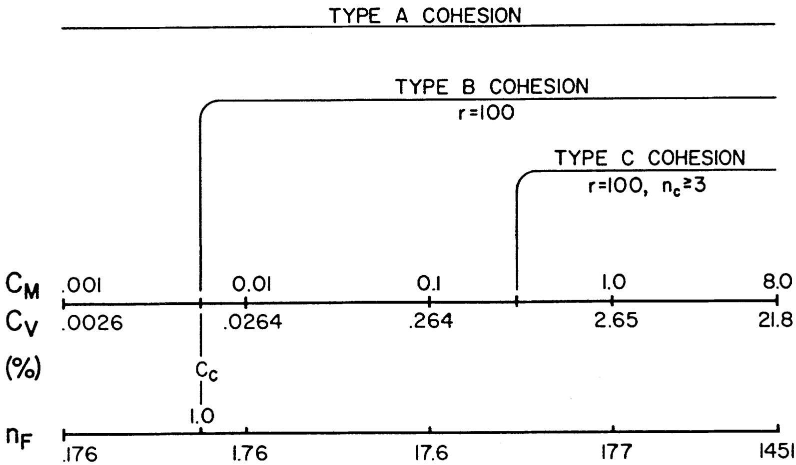


Fig 2—At consistencies commonly encountered in pulping and papermaking. Types B and C cohesion caused by mechanical entanglement exist along with Type A cohesion caused by electrostatic and electrokinetic forces. As consistency increases, Type B, and then Type C forces tend to become the dominant ones in the suspension.

Chemical additives are often introduced into pulp suspensions to improve retention (15). To be effective, however, they must impose very large Type A forces to withstand the high shear stresses imposed on fibre surfaces in the wet ends of modern paper machines (16). These forces may be sufficiently large to cause macro-flocculation as well (14). Alternatively, chemical additives called formation aids are sometimes added solely to decrease macro-flocculation. It is not certain how they achieve their effect, but in most cases they appear to lower the coefficient of friction between fibres (17), and hence diminish Type C cohesion. However, it has been suggested that some formation aids achieve their effect by changing the rheology of the suspending water (18).

2.3 Formation of Fibre Flocs

We now address the question of how flocs form. It is appropriate to begin with an unflocculated suspension well below the critical concentration. Thus, the first requirement is that fibres collide. This is commonly achieved by velocity gradients in shear flow which cause fibres to have relative motion in both rotation and translation. Observing fibre motion in very dilute fibre suspensions ($C_m < 0.05\%$) in shear flow, Mason (8,10) found that fibres collided and thereupon formed flocs. These flocs then dispersed completely, and the fibres then formed new flocs. Mason termed this transient state of flocculation "dynamic equilibrium". He observed it at concentrations near the critical concentration.

Above the critical concentration ($n_f > 1$), fibres are in frequent collision with other fibres. When $n_f > 66$ ($n_c > 3$), fibres are in networks and are therefore in continuous contact. Hence collisions are not required to create contacts between them. Rather, the imposition of relative movement between fibres disrupts existing contact points and creates new ones. This also leads to the formation of new flocs from old ones. This process of fibre rearrangement is commonly achieved by generating turbulence in the pulp suspension.

Flocs created by contact point rearrangement may also be transient or coherent in nature. Transient flocs occur when flocs completely disperse and new ones immediately form, that is, when the suspension is in a state of full dynamic equilibrium of the type observed by Mason below the critical concentration. Such transient flocs have been found to decrease in size with increasing intensity of turbulence (19,20). To attain this fully-dynamic state, fluid stresses must be sufficient to rupture all flocs completely, on a continuous basis. Given that high Type B and C cohesive forces and small flocs may exist in pulp suspensions, turbulence of high intensity and small scale is usually required to produce this state. When the turbulence decays, the transient flocs turn into coherent flocs, as will be discussed later.

An important point should be noted here. Turbulence in a pulp suspension is not synonomous with full dynamic equilibrium, as is often implied in the literature. Coherent flocs may also exist in turbulent flow. As defined earlier, these are flocs capable of sustaining themselves as coherent entities in the flow in which they are found. Some fibres may join and leave these flocs, but their growth and diminution are far from that observed by Mason in the case of "full dynamic equilibrium" (6).

Coherent flocs are likely to form from transient flocs in many of the unit operations of pulp and paper manufacture because these frequently have within them a common floc-forming flow: decaying turbulence. This flow is comprised of high turbulence in the wake of an obstruction followed by a field of decreasing turbulence downstream. Flows of decaying turbulence occur downstream of pumps, rectifier rolls in headboxes, pipes leading from well-agitated reservoirs, and even the plungers of laboratory sheet machines. However, despite the prevalence of decaying turbulence as a floc-creating flow, little is known about pulp flocculation in decaying turbulence (6). Early work showed that floc growth took place in this type of flow (22). Subsequent investigations measured the size of flocs using fibre optic probes (23,24) and determined the local intensity of turbulence from pressure fluctuations (25). We have also recently studied pulp flocculation in decaying turbulence in our laboratory.

We observed floc formation in the wake turbulence behind a grid using high-speed cinématography (26) and we measured turbulence intensities in this flow using laser anemometry (26,27). In suspensions of unbleached softwood kraft at C_m= 0.5%, we found that a state of dynamic equilibrium akin to that described by Mason could be attained when a sufficiently high level of turbulence was generated in the immediate wake of a grid (26). As the suspension flowed downstream, transient flocs from this high turbulence zone turned into coherent flocs in the decaying turbulence as illustrated in Figure 3. The coherent flocs originated in a zone of flow having substantial turbulence (26), and grew while moving relative to one another in a random fashion similar to that observed by Andersson (21). These observations support our earlier remark that turbulence is not synonomous with full dynamic equilibrium. Further downstream, all relative movement between fibres ceased, and the pulp suspension flowed in the plug regime.

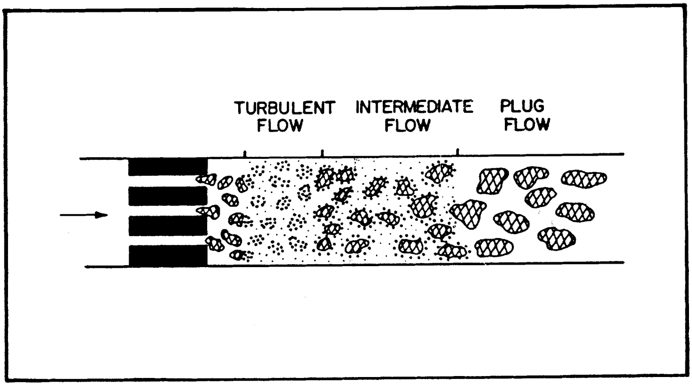


Fig 3—Illustration of pulp floc formation and the flow regimes in decaying turbulance. The dotted pattern represents transient flocs; the hatched pattern, coherent flocs (**6**).

In still more recent work, we examined floc formation in decaying turbulence at the fibre level. Turbulence was created in a suspension by moving a plunger through a 13mm deep plexiglas channel shown in Figure 4. Because no mean flow existed in the channel, floc growth could be viewed in a much smaller area than was possible in a system having a mean flow. Using high-speed cinématography, fibre and floc motion were photographed in a suspension of bleached softwood kraft pulp at $C_m = 0.3\%$. Observation of floc and fibre motion was facilitated by the use of tracer fibres created by dyeing approximately 10% of the pulp black. An area of 190mm x 130mm was filmed to observe floc motion; then, an area of 15mm x 10mm was filmed to observe individual fibre motion. The grid speed of 0.28 m/s produced a jet velocity of 1.3m/s from the grid openings.

As shown in Figure 5, a high degree of suspension homogeniety was attained at t = 0.20s. This time corresponds to the dimensionless distance x/d = 19, where x is the distance from the viewing point to the trailing edge of the grid and d is the size of the grid opening. As found in earlier work (26), the highest suspension homogeniety was observed at approximately x/d = 8. At this point, flocs ruptured into individual fibres

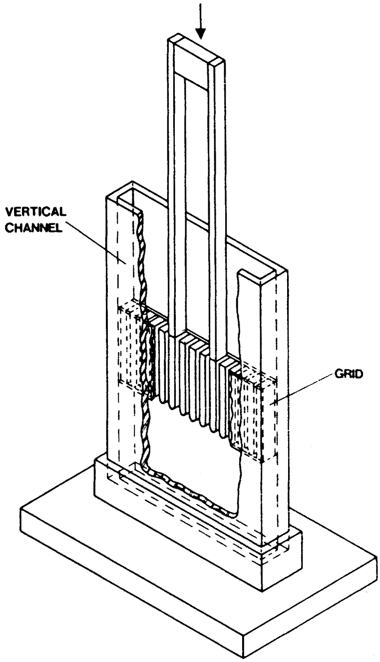


Fig 4—A grid is moved through a stationary channel to create a field of decaying turbulence having zero mean flow.

and new flocs formed. As the turbulence decayed with time, transient flocs turned into coherent ones, which grew in size and moved about in the turbulence. The suspension reached a state in which all fibre motion ceased at about t = 0.84s (x/d =77). At this time, the suspension had a very floccy appearance as shown in Figure 5.

Ciné-filming over the smaller area (15mm x 10mm) revealed that a state of full dynamic equilibrium occurred in the zone of highest homogeneity (x/d = 8). In this zone, individual fibres experienced substantial bending. Using the descriptive terminology of Forgacs *et al.* (2), fibres underwent flexible spins, followed by snake and loop turns. Such fibre bending is

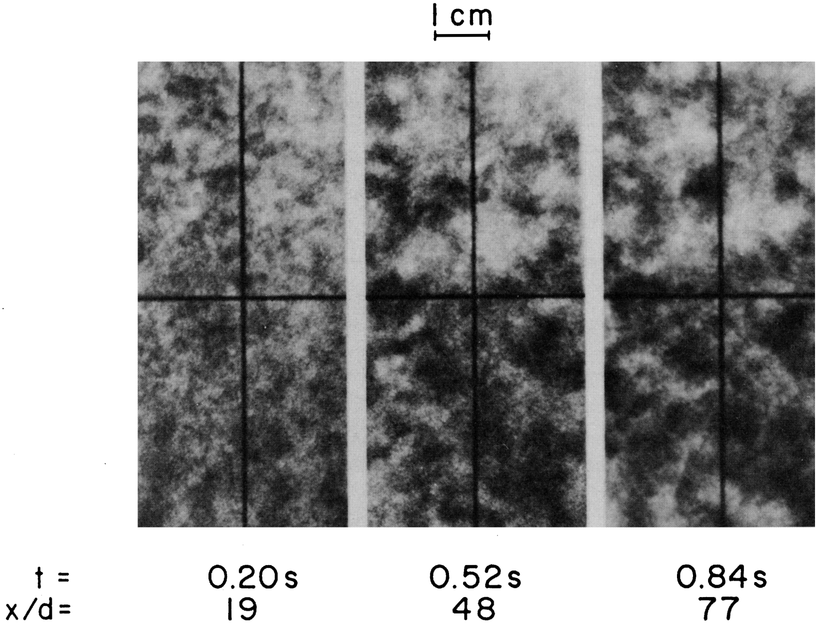


Fig 5—A sequence of frames from a ciné film showing the state of flocculation after passage of a grid through a stationary channel. The time (t) and corresponding dimensionless distances (x/d) after the passage of the grid are shown.

shown in Figure 6a. Traces of a sequence of fibre configurations are shown in Figure 6b. The fibre bending ceased around 0.13s (x/d = 12), just downstream of the zone of highest suspension homogeneity. This cessation of fibre bending appeared to coincide with first appearance of coherent flocs. Although the process of coherent floc formation could not be observed in detail, it is obvious that the formation of coherent flocs is closely linked to the cessation of fibre bending as described by Wahren *et al.* In summary, our findings confirm that fibre bending and dynamic equilibrium of the type observed by Mason below the critical concentration may exist above it as well if

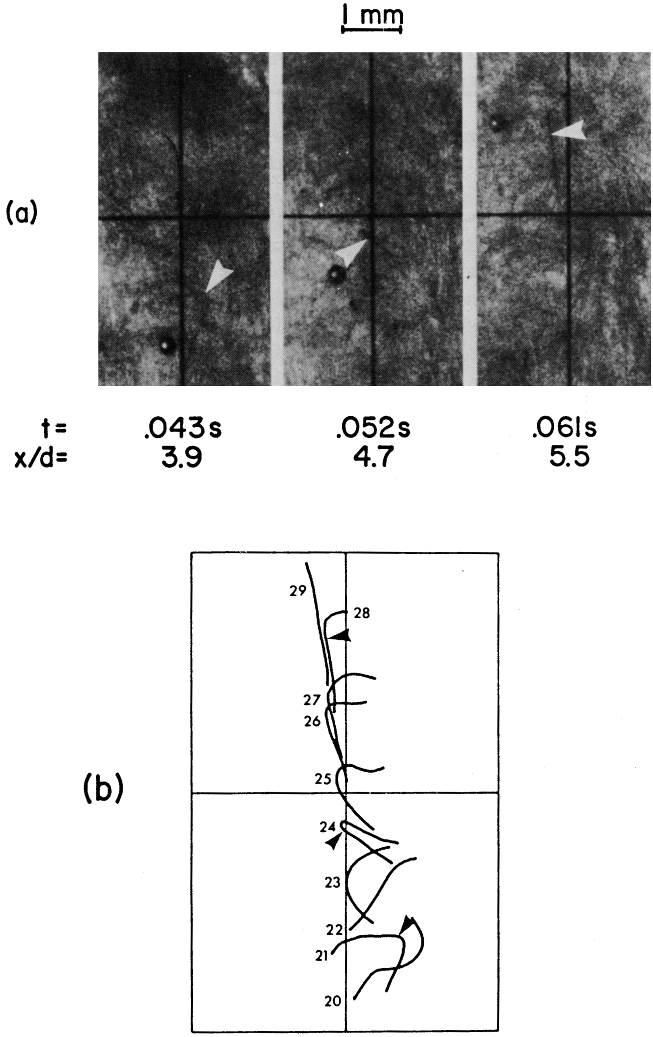


Fig 6—(a) A sequence of ciné film frames showing the motion of an individual fibre in a 0.3% pulp suspension in decaying turbulence. The time (t) and corresponding dimensionless distance (x/d) after passage of the grid are shown. (b) The decay of fibre bending is illustrated by traces taken from successive frames of the ciné film.

turbulence of sufficient intensity is generated in the suspension. The decay of this turbulence is linked to the formation and growth of coherent flocs.

The creation of coherent flocs in decaying turbulence is of considerable interest to papermakers because wake turbulence is commonly used to disperse pulp in headboxes However, as the turbulence decays downstream, transient flocs turn into coherent ones, and the pulp suspension becomes increasingly nonuniform as just described. This process is often referred to as reflocculation. It takes places quickly as shown by the experimentally-determined decay times given in Table I. These times were found to decrease with increasing consistency. However, a recent study at C_m= 1% and 2% (28) has concluded that decay time increases with consistency. This finding was attributed to decreased fibre mobility, and hence a decreased tendency for fibre entanglement. In most cases, however, the decay times are less than the time required for sheet forming in conventional papermaking. Consequently, the use of turbulence in headboxes to improve the formation of paper in conventional papermaking has been seriously questioned (29).

The magnitude of flocculation in flowing pulp suspensions has been measured by various light transmission and reflection techniques. These range from the earliest using ordinary light to more recent ones using fibre optics and laser beams. Spectral analyses of the light intensity signals have shown that a dominant floc size exists. Nerelius *et al.* (24) found it to be approximately 10mm; Egelhof (30) 6-12mm; Persinger and Meyer (31) 10mm; Norman (32) 7mm; Takeuchi *et al.* (33) 5-10mm. It is interesting to compare these findings to Wrist's (34) observation that floc size appears to be a characteristic of a given stock, the minimum dominant size being one to two times the longest fibre length. In the case of long-fibred chemical pulps, this would be approximately 5-10mm, about the level cited in the measurements described above.

Flocs may be created in flows other than decaying turbulence. For example, coherent flocs of substantial strength may be produced by stapling on the leading edge of an obstruction (6,34) or by prolonged rotation of a pulp suspension in an inclined cylinder. Using the latter method, Jacquelin (35,36) formed strikingly dense flocs that were virtually compacted

Table I. Reflocculation Time of Pulp Suspensions in Decaying Turbulence.

Investigators	Consistency C_m, %	Flow Velocity m/s	Reflocculation Time, s
Parker (23)	0.155	0.76-1.04	<2.0
Kallmes (81)	0.5	not given	0.5
	1.0		0.1
	2.0		0.04
	3.0		0.01
	4.0		0.001
Gundstrom (82)	3.0	not given	0.002-0.01
	4.0		0.001
d'Incau (27)	0.45	1.25-2.0	0.16
Takeuchi *et al.* (33)	0.14-0.86	0.83	0.5-1.5
Bonano (25)	1.0	7.6	0.007
		9.1	0.014
		10.2	0.012
	2.0	9.1	0.014
		10.2	0.012
Present work	0.3	1.3	0.13*
			0.84**

* - fibre bending stops
** - reflocculation ends

balls of pulp. Lee (37) found the mechanism of floc formation in this rolling method to be a two step process -- network truncation and compaction. The network first broke into aggregates; these then compacted into well-defined, dense flocs. The strength these flocs may attain is very great. This is illustrated by an observation made in our laboratory: dense nylon flocs produced by protracted rolling may be lifted from the suspension and held in air by grasping a single fibre protruding from the floc.

In summary, coherent flocs may form in different types of flow, and they can attain substantial strength. Few studies of the strength of individual flocs have been reported in the literature, but there are numerous studies of strength of fibre networks.

2.4 Tensile Strength of Pulp Networks

Forgacs, Robertson and Mason (2) pioneered the measurement of pulp network tensile strength. They used a pendant technique in which a pulp column extruding from a tube ruptured under its own buoyant weight. The plug breaking length was converted to a tensile rupture stress. Other studies using a similar technique at consistencies $0.3\% < C_m < 1.5\%$ followed (38,39,40,41,21).

As shown in Figure 2, Types A,B, and C cohesive forces may all exist in this LC range, although Types B and C have generally been found to be more important (38). However, there is another factor of key importance: the inherent non-uniformity of pulp networks. The low density zones around flocs have fewer contact points and therefore are weak zones in the network. Increasing non-uniformity thus makes the network weaker. Moreover, at the lower consistencies of this range, Type C cohesion may exist in flocs but not in the zones around flocs, thereby further weakening the network. Giese & Giese (39) demonstrated this importance of network uniformity by experiment: a pulp suspension first recirculated through a centrifugal pump to render it more uniform gave a stronger network than did a suspension of the same type recirculated through a displacement pump. Few other investigators, however, addressed the problem of network uniformity; they merely made the networks as uniform as possible. This also applies to the measurement of shear stress which will be discussed later.

Although experimental conditions differed among the various studies, the data may be combined to yield a correlation between the tensile strength, τ_t, of pulp networks and consistency. The data fit well to a power law equation of the type shown below:

$$\tau_t = a\ C_m{}^b \qquad (5)$$

where C_m is given in percent, and τ_t in Pascals. Specific values of a and b for the various investigations are shown in Table II.

2.5 Shear strength of networks

Numerous measurements of shear strength of fibre networks have also been reported in the literature. The point of network failure, however, has been interpreted in different ways. For example, some workers (42,43,44,45) measured a "disruptive shear stress" -- the stress required to disrupt the network permanently while others (13,46,47) measured an "ultimate shear stress" -- the maximum stress sustainable by a fibrous network subjected to increasing strain. Also, differing rates of strain were applied to the networks, and therefore viscoelastic properties of the pulp networks (48,49) may have caused variations in the strength measurements. Generally, however, the methods may be divided into two categories: quasi-static shear strength and dynamic network surface strength.

Quasi-Static Shear Strength

Measurements of this shear strength were carried out in viscometer devices which imposed increasing strain on the fibrous network from a smooth wall, from bristles protruding into the pulp network, or in one case from a cone immersed in the suspension (50). Although the conditions of the tests varied considerably, a useful correlation between shear strength and consistency may be obtained using the power-law relationship of equation (5). The values obtained for a' and b' in the various studies are shown in Table III.

Dynamic Network Surface Strength

When a pulp suspension moves relative to a smooth surface, under some conditions fibres may migrate away from the wall to form a clear annulus between the wall and the pulp network sur-

Table II. Tensile Strength of Pulp Networks.

$$\tau_t(\mathrm{Pa}) = aC_m(\%)^b$$

Investigators	Pulp Type	Freeness	a Pa	b
Forgacs *et al.* (2)	78% yield, beaten spruce sulphite	740 ml CSF	1.18	1.66
		662 ml CSF	1.20	1.26
		539 ml CSF	1.71	1.55
		440 ml CSF	1.19	1.63
		318 ml CSF	2.88	1.63
Chang and Robertson (38)	"standard" kraft, beaten	400 ml CSF	2.61	1.86
Giese and Giese (39)	chemical pulp	47° SR	1.75	1.86
		42° SR	1.42	1.38
	groundwood, centrifugal pump	52° SR	1.59	1.86
	positive displacement pump	52° SR	1.20	1.77
Veinov *et al.* (40)	no data given	19° SR	1.38	1.35
		42° SR	2.12	2.18
		AVERAGES	1.68	1.66

face (19). In pipes, this occurs in the plug flow regime. As the relative velocity between the wall and the plug increases, the shear in the annulus eventually becomes sufficient to rupture flocs and fibres from the plug surface. Numerous authors

Table III. Shear Strength of Pulp Networks in Quasi-Static Tests.

$$(\text{Pa}) = a'C_m(\%)^{b'}$$

Type of Test	Pulp Type	References	Avg. Values a' Pa	b'
disruptive shear stress	bleached and unbleached softwood	42,43,44,45	13.1	2.46
ultimate shear stress	krafts and sulphites	14,46,47	2.87	2.24
disruptive shear stress	bleached and unbleached softwood	42,43,44	3.90	2.96
ultimate shear stress	krafts and sulphites	14	1.96	1.69
disruptive shear stress	groundwoods	44	2.36	1.69
ultimate shear stress	groundwoods	14,47	1.78	2.25

have called this a "disruptive shear stress". It commonly occurs near the condition at which transition to turbulence takes place in the clear water annulus, and therefore some authors have termed it a "dispersive shear stress". It marks the beginning of network disruption into individual flocs and fibres that may move relative to one another just as fluid elements would. This state may be termed "pulp fluidization".

In a recent study (51), a "fluidizing shear stress" at which a pulp suspension in a vessel becomes turbulent was shown to agree well with the dispersive shear stresses measured in pipe flow (51). These various shear strengths are summarized in Table IV.

2.6 Rupture of Pulp Flocs

Having discussed the formation and strength of pulp networks, we will now discuss their dispersion. In particular, we will focus on the dispersion of flocs, since these may be considered local networks of high strength. To obtain a uniform suspension, it is necessary to disperse flocs into individual fibres.

In an extensive series of investigations, Mason and coworkers (52) examined the dispersion of various types of aggregates in shear flows at low Reynolds numbers. While these aggregates were generally less complex than pulp flocs, useful findings applicable to all types of floc rupture were gained. In particular, Kao and Mason (53) found that irrotational shear flow was more effective in dispersing aggregates than was rotational shear flow. This finding suggested that elongational flows, which stretched aggregates but did not rotate them, were more effective in dispersing aggregates than ordinary shear flows which tended to rotate them. As discussed previously, Jacquelin's work has shown that rotational flows may strengthen flocs rather than disperse them.

Kerekes (54) examined floc dispersion in one of the commonest elongational flows found in process equipment -- entry flow to constrictions. Flocs of long-fibred pulp were found to stretch and, if stretched sufficiently, to rupture as shown in Figure 7. However, the elongational strain necessary to achieve rupture could only be produced by constrictions having openings much smaller than the floc size. Thus, the walls of the constriction restrained floc movement, and floc rupture could not therefore be ascribed entirely to the hydrodynamic elongational strain in the entry flow. Nevertheless, it was found that stretching by a ratio of at least 5:1 was required to rupture flocs of unbleached softwood kraft in a suspension of $C_m = 0.5\%$. The time of application of the strain was also found to be important, indicating the influence of network viscoelasticity on

Table IV. Shear Strength of Plug Surfaces in Flowing Suspensions.

$$\tau(\text{Pa}) = a''C_m(\%)^{b''}$$

Type of Test	Pulp Type	References	Avg. values a'' Pa	b''
Plug surface disruption in pipe flow - "disruptive shear stress":				
a) visually assessed plug radius	bleached kraft from pine	44,42	20.0	2.18
b) plug radius determined from velocity profiles	bleached kraft	44,42	10.9	2.66
	hardwood kraft	83	5.25	2.76
c) shear stress at the pipe wall at the onset of turbulence in the water annulus	sulphites, soda, kraft, and groundwood	23,84	3.02	2.50
Onset of drag reduction in pipe flow - "dispersive shear stress"	chemical softwoods	85,86,87, 88,89	4.5	1.69
	hardwood soda	90	4.7	3.02
	TMP	91	4.34	2.57
	groundwoods	87,92,93	1.86	2.00
Onset of complete turbulence in double cylinder tester	pine krafts	51	24.5	2.00
	groundwood		6.7	2.43

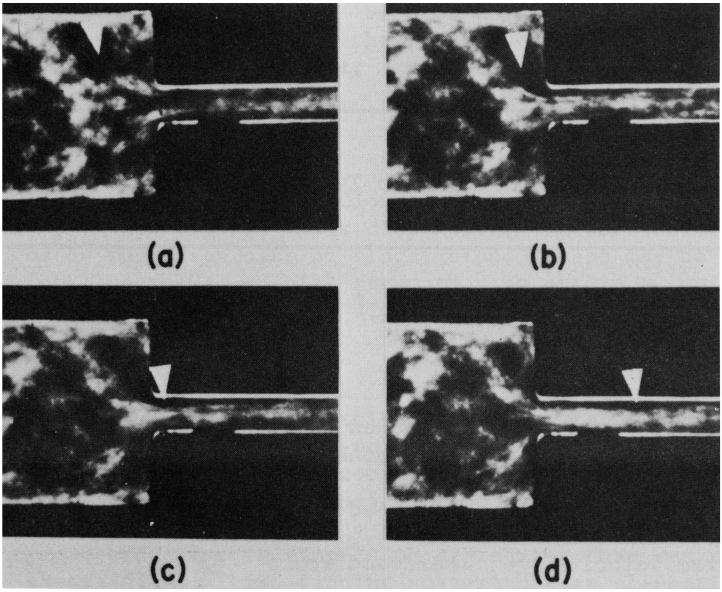


Fig 7—A sequence of frames from a ciné film showing the stretching of an individual floc entering an 8mm constriction (**54**)

floc dispersion. Similarly, Duffy and Norman (55) found that long-fibred pulps flowing in contracting channels sustained large elongations without rupture, whereas short-fibred mechanical pulp ruptured readily. In contrast to these results, Takeuchi *et al.* (33) found that flocculation increased, that is, flocs grew in size in converging channels. This interesting finding clearly warrants further study.

In recent work, we examined floc dispersion in a more complex flow than the one just described. The flow consisted of two stationary counter-rotating vortices in a 13mm deep channel. Dense flocs produced by stapling on the leading edge of a protrusion passed into the zone between these two vortices as shown in Figure 8. The movement of fibre flocs through this flow field was filmed using a high-speed ciné camera at a framing rate of 400pps and shutter speed of 1/2500s.

A typical sequence of events leading to floc dispersion is shown in Figure 9. A floc passing between the vortices became partially entrained in each vortex. The floc, stretched and distorted by the stresses imposed by the vortices (Figure 9b), then broke into several fragments (Figures 9c and 9d). Some of these were swept downstream, but others remained in circulation within each vortex (Figures 9e and 9f). Usually, the fragments circulated for several revolutions before becoming re-entrained in the main flow. On passing into the main flow, the fragments elongated rapidly and disintegrated as they were swept downstream.

Vortices of the size and strength produced in these experiments (approximately 10mm and 6×10^{2} m^{2}/s) were sufficient to rupture flocs into several fragments, but not to disperse them

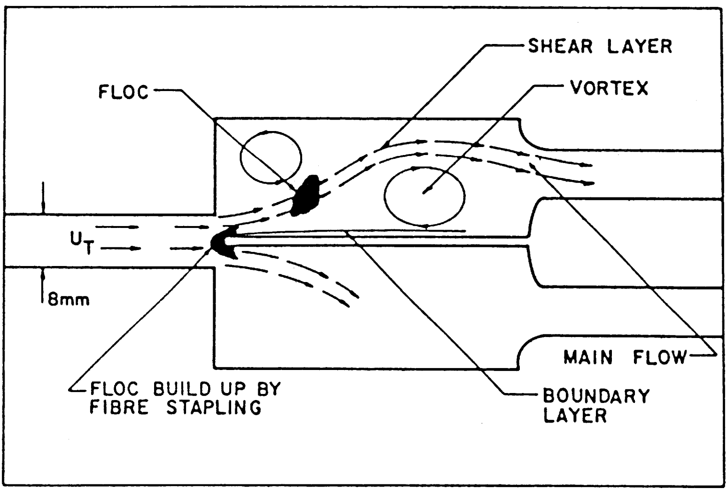


Fig 8—A flow field in which flocs form on the leading edge of an obstruction and shed into a flow containing two counter-rotating vortices.

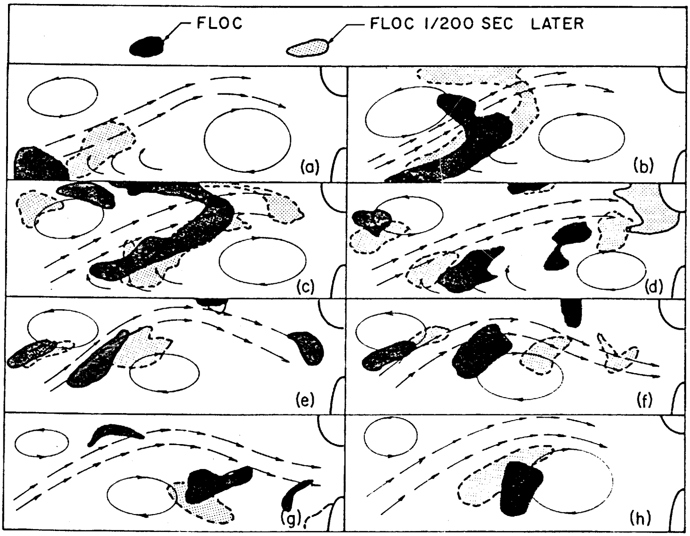


Fig 9—A sequence of frames from a ciné film showing the deformation and rupture of a floc flowing between two counter-rotating vortices.

completely. Dispersion was achieved more effectively in the thin shear layers at the edge of the vortices. In earlier work we noted a similar behaviour when flocs passed through shear layers on emerging from the channels of a grid into wake turbulence. We concluded that such shear layers imposed the highest level of shear on individual fibres in the entire turbulent wake flow (16). The findings described here confirm these earlier observations regarding the effectiveness of shear layers in floc dispersion.

In other recent work, Lee (37) investigated floc dispersion in turbulent Couette flow. Using high-speed cinématography, he observed the dispersion of single, compacted flocs produced beforehand by the rolling method described earlier. He found that flocs first broke up by large-scale fragmentation, and then by small-scale erosion of individual fibres from the fragments. To fragment flocs, a tensile force greater than the strength of the floc and a strain greater than the "minimum fibre separation required for rupture" had to be applied. The subsequent erosion step was found to be a rate process. Complete floc dispersion was therefore time dependent; the time required decreased as the turbulent stress level increased.

The investigations just described have increased our knowledge of how flocs rupture in various flows, but our ability to predict the flow conditions at which they rupture is still very limited. This is particularly true for the most common flow used for this purpose -- turbulence. This flow is stochastic in nature and therefore the stresses and strains in it cannot be defined with the exactitude of laminar flows. Nevertheless, progress has been made in other fields using the power dissipation to characterize the levels of tensile and shear strains imposed on aggregates by turbulence. By relating these turbulent stresses to the rupture stresses of aggregates, approximate predictions of floc dispersion at various scales have been made (56,57).

Power dissipation may also be used to characterize the turbulence required for dispersing pulp flocs. It is particularly useful in characterizing the turbulence required to achieve dynamic equilibrium in pulp suspensions. As discussed earlier, transient flocs in this state give a more uniform suspension than do coherent flocs. Also, as discussed earlier, fibres and flocs in this dynamic state move relative to one another as would individual fluid elements. Accordingly, the pulp suspension is "fluidized". The suspension adopts the properties of a simple fluid in this state. For example, while pulp suspensions in plug flow at low velocity have unusual friction loss characteristics, in turbulent flows at high velocity their friction loss behaviour approaches that of a Newtonian fluid. The importance of this fluid-like behaviour of pulp suspensions will be discussed later.

Fluidization of pulp suspensions may be achieved by applying turbulent stresses large enough to rupture fibre networks completely on a continuous basis. Turbulence having a high intensity and small scale can achieve this objective. The energy associated with this turbulence is ultimately dissipated as heat. Accordingly, power dissipation can be used as a measure of whether or not fluidization is achieved in a pulp suspension.

Wahren (5) employed the concept of power dissipation to predict fluidization in pulp suspensions. By relating the shear stresses associated with power dissipation to the disruptive shear stresses at pulp network surfaces, he obtained an estimate of the power dissipation, P_f, required for pulp fluidization,

$$P_f = 11.6 \times 10^3 \, C_m^{\ 5.28} \tag{6}$$

In this equation, P_f is in W/m^3 and C_m is in percent.

Equation (6) has not been tested beyond $C_m = 6\%$, but below this level it appears to agree well with the power dissipation required to obtain substantial improvement in fibre uniformity in high consistency forming (5). However, recent laboratory measurements of pulp fluidization by Gullichsen and Harkonen (51) suggest that pulp fluidization takes place at values of P_f approximately three orders of magnitude lower than those predicted by equation (6). There is no obvious explanation for this discrepancy, but it is probable that a spectrum of pulp fluidization levels may exist, from the level of individual fibres to the level of flocs or aggregates of flocs. It is possible that the lower levels of power dissipation found in (51) represent fluidization at the floc level, whereas those of Wahren represent fluidization at the fibre level. However, as pointed out by Wahren (5), "the nature and extent of fibre interactions in this dynamic state are largely unknown; its importance suggests that it is a topic worthy of investigation."

3. FLOCCULATION AT MEDIUM CONSISTENCY (8-20%)

Medium consistency (MC) pulp suspensions are of growing interest in pulp and paper technology. Storage, pumping, mixing and screening are increasingly being carried out in this range (58).

The first factor of importance in flocculation within this range is the very high concentration of fibres, which gives a very high level of inter-fibre contact. For example, for C_m = 10%, r = 100, and a zero void ratio, n_f = 1800. This corresponds to n_c= 24 if equation (3) applies. Such a high level of contact and the corresponding level of fibre bending to accommodate this contact suggests that Type C forces are predominant. Flocs at this consistency protrude readily from the suspension surface as shown in Figure 10.

A second factor of importance in MC pulp is that under ordinary conditions substantial air is present in the suspension. This is to be expected because MC suspensions are produced by vacuum dewatering and then fluffing. Thus, consistency alone is no longer a measure of fibre concentration: the fractional volume of air, the void ratio, ε, also determines this. Values of ε may vary considerably. For example in the bulk state at C_m= 19%, ε can vary between 6 and 35% (59). In the dispersed state, $\varepsilon \longrightarrow 1$.

Fig 10—A medium consistency suspension containing a mixture of bleached and unbleached softwood kraft pulp at C_m = 10%

The presence of air in MC pulp has important ramifications for flocculation. The air-water-fibre interface at fibre interstices produce strong Type D cohesion, which adds to the substantial Type C cohesion already present. Indeed, as ε increases the very nature of flocculation changes, from mass concentrations of fibres in water, to water-fibre aggregates surrounded by voids. Just as LC fibrous networks rupture at their weak points, so MC suspensions will rupture at their weak points -- the voids surrounding water-fibre flocs. Hence, the suspension ceases to be a continuous network. With increasing ε, an MC suspension changes from a porous medium containing gaseous bubbles, to a permeable medium containing fibre-water aggregates surrounded by gas voids, and finally to a dispersed phase system when the fibre-water aggregates are suspended in a large volume of flowing gas.

Increasing amounts of air cause significant changes in the rheology of MC pulp suspensions. The suspensions become compressible; thus energy from pumping is expended on compressing the pulp suspension (59). When the air content is greatly increased, the flowing suspension becomes one of pulp in pneumatic transport. In this regime, decreasing consistency and increasing velocity leads to a decrease in floc size (60). Increasing air content also leads to an increasing tendency toward phase separation when the suspension is subjected to centrifugal or gravitational forces normal to the flow direction. The water-fibre aggregates separate readily from the surrounding air owing to their large inertia relative to the suspending medium. This effect will be more fully discussed in the later section on dry fibres.

The high network strength gives MC pulp suspensions solid-like properties, and for this reason MC suspensions are conventionally transported by displacement pumping (59,61). However, recent work (62) has shown that if air is removed from the suspension and a sufficiently high shear stress applied, MC suspensions may be fluidized to a sufficient degree to permit centrifugal pumping. Moreover, the levels of shear stress required to fluidize deareated MC pulp suspensions were found to be extrapolations of the dispersive shear stress measured in low consistency pulp suspensions (51). This recent discovery has led to the development and rapid implementation of centrifugal pumps for transporting MC pulp (58), whereas previously only displacement pumps could be used for this purpose.

4. FLOCCULATION AT HIGH CONSISTENCY (20-40%)

High consistency (HC) pulp suspensions are usually produced by pressing water from a pulp pad and then fluffing the pad by mechanical means. The resulting pulp is a three-phase system of water, fibres, and air. As the consistency increases from 20% to 40%, the amount of free water diminishes, eventually falling below the fibre saturation point.

HC pulp tends to have large void ratios even when in a rest (bulk) state. For example, the bulk density, ß, (mass of dry fibre divided by the volume of the suspension) in an uncompressed bed of chemical pulp of $C_m = 30\%$ is approximately 30-70 kg/m^3. This gives $\varepsilon > 0.90$. However, despite this low bulk density, the volumetric concentration of fibres is high. For example, for $ß = 30$ kg/m^3, $n_f = 180$. However, fibres are concentrated in water-fibre aggregates, which occupy only a small fraction of the suspension volume. The estimated value of n_f in these aggregates is much higher, in this case $n_f = 670$.

The high void ratios and locally high concentrations of fibres suggest that Type C and Type D cohesive forces predominate. No measurements of floc strength of HC pulp have been reported in the literature, but studies of wet web strength have shown that Type D forces are the principal factor in determining network strength up to the consistency at which free water still remains in the network (63,64,65). Wet webs, being layered fibrous structures rather than three dimensional networks, differ substantially from fluffed HC pulp suspensions, but it is nevertheless reasonable to expect that Type D forces contribute substantially to the strength of HC pulp suspensions as well.

In the dispersed state, HC suspensions become a heterogeneous mixture of water-fibre aggregates suspended in a gas. Such suspensions are found in flash-drying, oxygen bleaching, and mechanical pulp refining. An example of an HC suspension discharging from a TMP refiner is shown in Figure 11. The suspension is clearly very flocculated. In this high consistency range, the flocs of practical interest, even in the bulk state at rest, are water-fibre aggregates fully or partially surrounded by connected voids. Accordingly, the state of flocculation may be characterized by an "aerodynamic specific surface", S_a. This is a measure of the specific surface of fibre

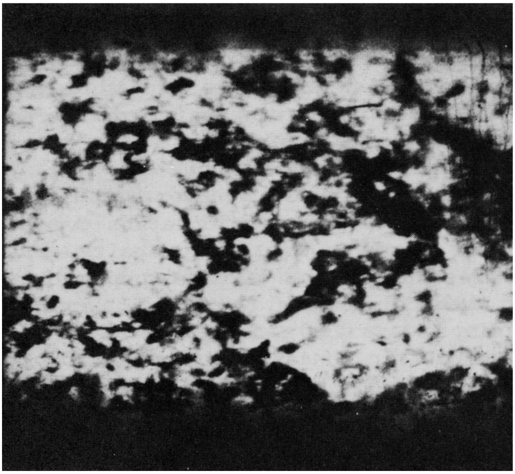


Fig 11—Softwood mechanical pulp suspended in steam in the discharge of a TMP pilot refiner (C_m = 36%)

aggregates that are impermeable to a slowly moving gas through a bed of pulp, as illustrated in Figure 12 (66). Values of S_a may be determined by a permeability method analogous to that used to measure hydrodynamic specific surface (66,67). Typical values of S_a for HC pulp are given in Table V. With increasing consistency, S_a passes through a maximum at approximately 35% (66), but generally the values for all HC pulp fall in the range 20-60 m^2/kg. This range is considerably lower than the values of S_a for individual fibres, which can be estimated from the hydrodynamic specific surface of individual fibres to be about 1000 m^2/kg. (66). Given the strong cohesive forces in HC pulp discussed earlier, HC flocs are difficult to disperse by aerodynamic forces, and even by mechanical forces. Suspensions of HC pulp are therefore likely to remain quite flocculated, that is, retain a low S_a in the dispersed phase as well.

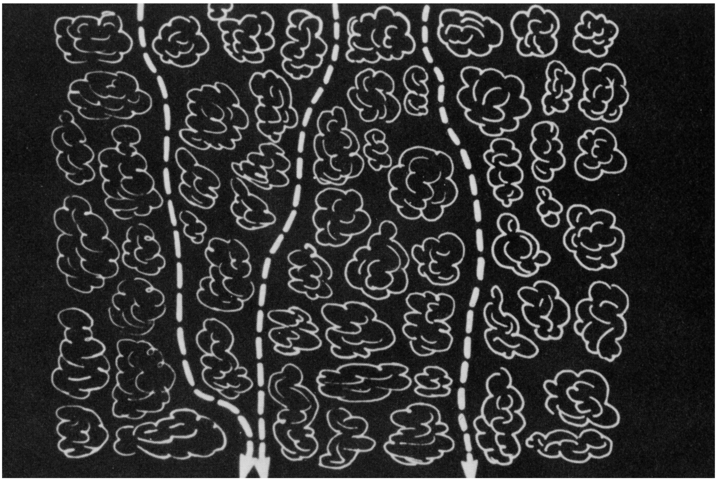


Fig 12—An illustration of gas flow through a bed of high consistency pulp. The surface area of the fibre aggregates seen by the gas flow is the "aerodynamic specific surface" of the pulp.

5. ULTRA HIGH CONSISTENCY FLOCCULATION (40-90%)

As pulp consistency increases beyond 40%, fibres pass through a critical moisture content at which free water is completely evaporated from their surfaces. Only imbibed water remains (63). During this evaporation process, water bridges between the fibre surfaces impose strong Type D cohesive forces that induce hydrogen bonding as drying proceeds to completion. Thus, hydrogen bonding supersedes Types A,B,C and D cohesion as the major cohesive force between fibres in flocs. When hydrogen bonding is absent, the dominant cohesive force in UHC flocs is determined in part by the history of the fibres: if the pulp is dried to a level below the fibre saturation point and then fully dispersed, the pulp flocs behave as very strong HC flocs; on the other hand, if the pulp is dried beyond the fibre saturation point, and then dispersed, the pulp merely behaves as a suspension of very flexible fibres.

Table V. Aerodynamic Specific Surface of Pulp.

Condition	Pulp Type	C_m %	Aerodynamic Specific Surface (m^2/kg)
a) Pinwheel fluffed: (<u>66</u>)	Softwood TMP1	36	61
	TMP2	31	47
	RMP1	34	50
b) Pinwheel fluffed; dried in situ: (<u>66</u>)	Softwood TMP3	20	21
		30	40
		66	33
c) As received:	Softwood RMP2	95	68
Dry refined*: (unpublished work)			223
Pinwheel fluffed:	Bleached Softwood kraft	95	15
Dry refined*: (unpublished work)			458
d) Calculated:	Cylinder of dimensions of undelignified pulp fibre		350
e) Hydrodynamic Specific Surface (<u>67</u>)	Sulphite pulped softwood		1330

*<u>Refiner Conditions</u>		RMP2	BSK
Plate Gap	mm	0.127	0.127
Feed Rate	g/s	19	5
Fluffing Energy	MJ/kg	0.23	1.0

Prior to dry refining, the RMP was air-dried as received from the open discharge refiner. The dry lap BSK was reslushed, dewatered to approximately 40% solids, pinwheel fluffed and air-dried.

6. FLOCCULATION AT "DRY" CONSISTENCY (90-100%)

Individual fibres are produced from dried pulp by defibration in mechanical devices such as disc refiners or hammer mills (68). The creation of individual fibres from dried aggregates increases the aerodynamic specific surface of the pulp by approximately ten-fold as shown in Table V. However, dry fibres also aggregate into flocs when in suspension as illustrated in Figure 13. The flocs remain when the pulp is in a rest state as well, as shown in Figure 14.

Garner (69) recently measured the tensile strength of dry pulp flocs. He found their strength to vary with concentration according to the following relationship:

$$\tau_t \propto C_v^{\,2.24} \tag{7}$$

It is interesting to note that the value of the exponent, 2.24, is approximately equal to the values shown earlier for LC pulp suspensions (Tables II and III). This agreement between the exponents of LC and dry pulps suggests that mechanical forces (Types B and C cohesion) are the major factors determining floc strength in both cases (69). This is also suggested by the observation that n_f has comparable values in both cases. For example, in the dry case at typical bulk densities of 12-76 kg/m^3, n_f = 55-345. In the wet case, this range of n_f is attained in the consistency range $1\% < C_m < 2\%$, as shown in Figure 2. However, whereas Type C cohesion is dominant in LC suspensions, in the case of dry fibres Type B cohesion may be of greater importance owing to the contorted nature of the fibres and their stiffness (69). This is suggested by the fact that flocs of softwood chemical pulps are approximately ten times stronger than those of mechanical pulps, and by the very high elongational strains to rupture shown by the dry flocs (69). It appears that fibres repeatedly lock and unlock on sliding past one another during floc straining. Such behaviour is suggested by the jagged nature of the stress strain curves (69).

After mechanical defibration, dry fibres suspended in a flowing gas tend to flocculate. In applications such as dry forming, it is necessary to produce a uniform suspension of

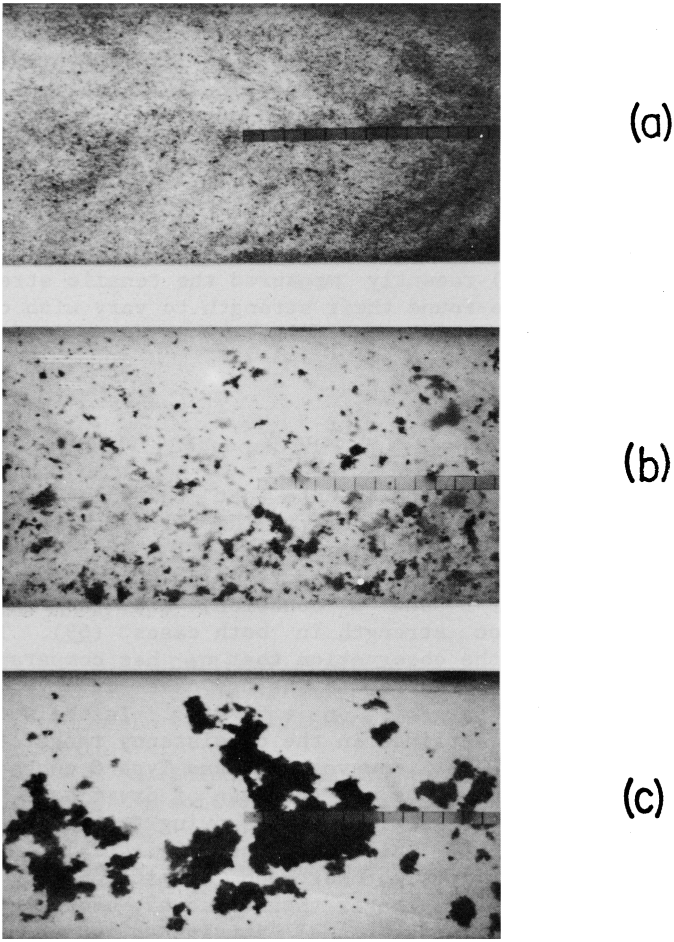
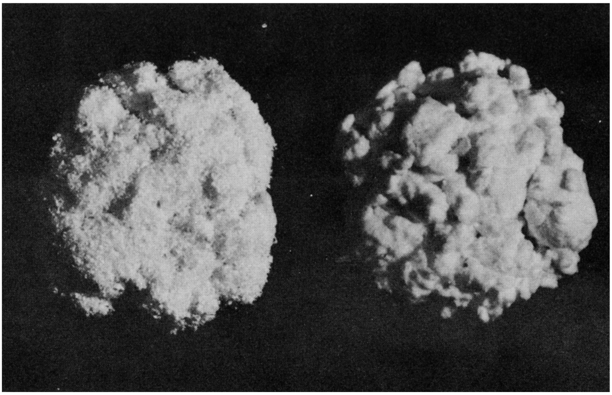


Fig 13—Comparison of fibre flocculation in air suspensions: (a) softwood refiner mechanical pulp; (b) bleached hardwood kraft; (c) bleached softwood kraft at a flow velocity of 45 m/s and a concentration of 98 g/m^3 in fully developed pipe flow (**71**)



(a) (b)

Fig 14—The appearance of bleached hardwood kraft pulp before and after dry refining. The small bonded aggregates evident in (a) are dispersed by refining to give a pulp containing mostly individual fibres in large unbonded aggregates (b) (**66**)

fibres. To achieve this, many of the considerations discussed earlier for the dispersion of aqueous pulp suspensions also apply to this aerodynamic case.

To attain a uniform suspension of dry fibres, pulp flocs must be ruptured and then dispersed into individual fibres. Given the substantial strength of dry flocs, aerodynamic stresses are often insufficient to achieve this (70). Dispersion is usually attained by mechanical means, often by the device used to inject the pulp into the gas flow. However, even after mechanical dispersion, long-fibred pulps tend to flocculate when suspended in air. Typical suspensions of mechanical and chemical pulps injected into a straight pipe using a blower (71) are shown in Figure 13. It can be seen that the mechanical pulp was dispersed almost completely, whereas the chemical pulp remained very flocculated. Aerodynamic forces can, however, affect flocculation to some extent; for example, it has been found that flocs near the centre-line of pipe flow are generally larger than those in the high shear zones near the pipe wall (72). In summary, flocs of dry pulp, particularly long-fibred pulps, have considerable strength and must be dispersed by mechanical means in most cases.

Once dry pulp flocs are dispersed, individual fibres tend to flocculate just as they do in the case of aqueous suspensions. To avoid this, extreme dilution is commonly employed in both cases. For example, a concentration of 0.8g/cm^3 has been cited as an optimum level for cotton fibres (73). For a cotton density of 1.55 g/cm^3, and a typical value of r = 1000 (74), this concentration corresponds to C_v=5.2 x 10^{-7}, and n_f = 0.34. This value of n_f is below the "critical concentration" discussed earlier. For dry pulp fibres, a volumetric concentration of C_v= 2.5x 10^{-3}% has been cited as a suitable level for minimizing flocculation (75). This concentration corresponds to n_f = 0.17. Thus, the concentrations of dry fibres in air suspensions that minimize flocculation are below the critical concentration defined earlier.

Because of their large inertia relative to the surrounding gas, fibres suspended in gases have a strong tendency to phase separation when forces perpendicular to the flow act upon them. For example, phase separation occurs readily from centrifugal forces during flow through bends (76). Such phase separation leads to a "stratified flow" in which the fibres concentrate along one wall of the channel. The level of stratification together with the degree of flocculation define the four flow regimes in which gas-fibre suspensions may flow (71). These regimes are illustrated in Figure 15.

Phase separation causes fibres to concentrate locally, and this in turn may increase flocculation substantially. As flocs form they move slower than the surrounding suspension, causing ever more fibres to join them. This may lead to a cascading growth that produces flocs as large as the channel cross-section. An example of such flocs is shown in Figure 16. Continued recirculation of the suspension in a closed loop under these conditions may eventually produce slug flow, that is, a

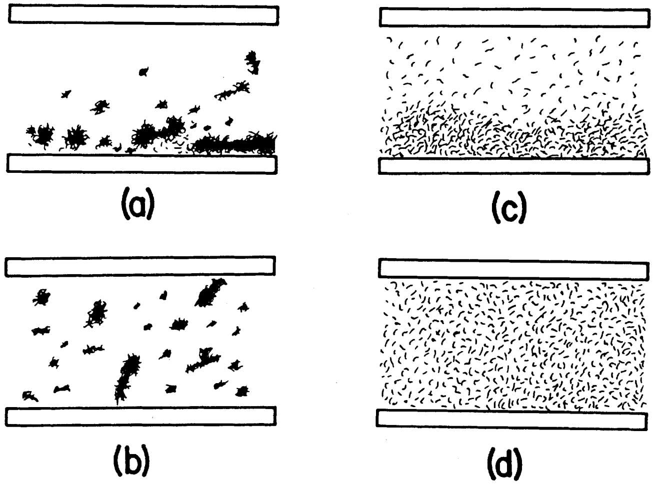


Fig 15—Flow regimes of pulp fibres in a gas suspension: (a) Heterogeneous (poor floc dispersion); (b) Flocculated (poor floc dispersion; good distribution over channel cross-section); (c) Stratified (good floc dispersion; poor distribution over channel cross section); (d) Homogeneous (good floc dispersion; good distribution over channel cross-section).

flow which alternates between slugs of fibres and fibre-free air. Such slug flows have also been observed in pneumatic transport of MC pulps (60).

7. SUMMARY

This paper has discussed some of the key factors that govern the state and process of fibre flocculation over the entire range of consistency found in pulp and paper manufacturing. They are: the number of contacts between fibres, the cohesive forces at these contacts, and the stresses supplied by the suspending fluid.

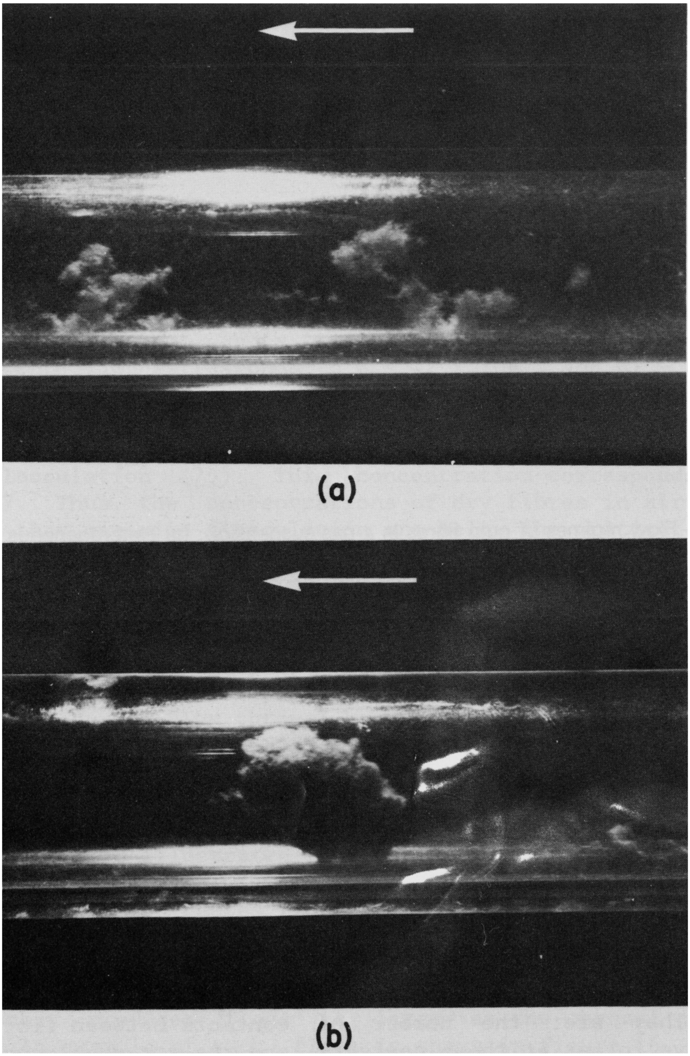


Fig 16—Air suspension of a dry refined thermomechanical pulp at a fibre concentration in air of 350 g/m^3. (a) Fibre suspension just before the pipe bend consists of a dispersion of fibre flocs surrounded by individual fibres. (b) Fibre suspension just after a 180° bend consists of flocs that have been rolled into almost spherical aggregates during the passage around the bend.

The number of contacts, and the collisions leading to contacts, are strongly influenced by the degree of interaction experienced by fibres in rotational movement. A simple and useful indicator of this level of fibre contact is the number of fibres, n_f, in the volume swept out by a single fibre length. When n_f is less than one, softwood pulp fibres in water suspension and dry fibres in air suspension flocculate little. Increasing n_f leads to increased collisions between fibres in flowing suspensions. When n_f is greater than about 70, softwood pulp fibres suspended in air or water form networks, that is, they are in continuous contact even when in flow. The fibres, however, are never uniformly distributed in such networks; they are always present in mass concentrations called flocs. With increasing levels of n_f, aqueous suspensions of fibres reach consistencies at which substantial amounts of air appear in the suspension. The flocs of consequence in this three phase system are water-fibre aggregates surrounded by air.

Four types of cohesive forces may exist at fibre contact points over the entire range of consistency, but their relative importance changes. For example, at low consistency in water and at very high consistency (dry) in air, Types B and C forces caused by mechanical entanglement generally dominate over electrokinetic and electrostatic forces. At intermediate consistencies, where both water and air exist, Type D forces caused by surface tension are present along with Types B and C forces, and generally dominate. The cohesive forces at all consistencies give the networks and flocs mechanical strength.

Hydrodynamic, aerodynamic, or mechanical stresses may rupture pulp networks at their weak points and thereby create flocs. These may act as independent entities called coherent flocs. Larger stresses disperse these flocs into individual fibres. The degree of floc dispersion attained in a flowing system is dependent on the relative strength of the flocs and the magnitude of the applied stresses. For example, strong hydrodynamic stresses applied to weak Type A flocs give substantial floc dispersion, whereas weak aerodynamic forces applied to flocs held together by Types B, C, D cohesion barely rupture them at all.

8. CONCLUDING REMARKS

This paper has emphasized current understanding of fibre flocculation rather than its effects on the unit operations of pulp and paper manufacture. In some cases the latter are well-known. For example, in the forming zone of a paper machine flocculation leads to a non-uniform mass distribution in paper. However, the effect of flocculation on other unit operations is less well understood. For example, although flocculation has long been cited as an important factor in screening and cleaning, no scientific studies of its effect on these processes may be found in the literature. In mixing, work has only recently begun to determine microscale uniformity attained by mixing at the floc level (77). Some progress has been made in understanding the role of flocculation in pulp refining; its effect was identified long ago (78) and more recent work has confirmed its importance (79,80).

In summary, our knowledge of pulp fibre flocculation is growing, but much work remains to be done to improve our fundamental understanding of this important topic. Even more work is required to understand its effect on some of the key unit operations of pulp and paper manufacture.

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Transcription of Discussion

The Flocculation of Pulp Fibres
by R.J. Kerekes, R.M. Soszynski and P.A. Tam Doo

Hossain What would you expect if, instead of water, you carried out these experiments in a non-polar medium such as pentane or hexane? Also, if you acetylate the pulp and then use a polar medium like water, would you not expect to observe differences in flocculation behaviour.

Dr. R.J. Kerekes I have a graduate student currently studying flocculation of straight fibres in sugar solutions and other liquids. The process of flocculation holds even though there is no "hooking" action. In fact nylon fibres can form flocs so strong that you can lift them from the liquid by grasping one fibre. Chemical additives and differing suspending fluids such as those you suggest can affect flocculation substantially. We hope to study these factors as well.

Dr. D. Reeve University of Toronto, Canada

We are interested in medium consistency mixing, in bleaching in particular, and we have been looking at the stability of flocs in very high shear regimes. We find that flocs are surprisingly stable. A blob of red pulp which contained about 1000 flocs, introduced into the mixer broke up by sub-division initially but after 10 seconds a significant number of small flocs still remained. So it appeared that the elementary entities in the suspension under these "fluidised" conditions are flocs and not individual fibres. This information will be significant in bleaching.

Kerekes I think a spectrum of fluidization levels may exist. As the strength of flocs increases under the same hydrodynamic conditions, there may only be fluidization at the floc level whereas with weaker fibres, there may be fluidization at the fibre level.

Reeve From our observations we have considerable evidence to show that within our mixer we obtained long-lived stable flocs.

Prof. J. Marton Westvaco, Laurel, USA

Do you have any information about the tendency of curled fibres to flocculate?

Kerekes As I mentioned earlier, we are now in the process of isolating the various factors that affect flocculation. We plan to obtain such information.

Atalla Your pictures of the effects of turbulence on fibre dispersion reminded me of melting nucleation and crystallisation of a polymeric material. Do you see any parallels between these two phenomena?

Kerekes Yes, I can see some analogy.

Dr. J. Mardon Omni Continental, New Westminster, Canada

You have measured the turbulent intensities with a laser doppler anemometer but you do not mention whether you have tried to correlate the effect of scale and the intensity with the amount of flocculation. Burcell and Shuffler indicated that flocculation would increase with increasing intensity of turbulence, which is contrary to "conventional wisdom" although in agreement with the experience of many practical papermakers.

Kerekes A colleague of mine at the Institute, S. d'Incau, has carried out such experiments. He observed flocculation and measured turbulence intensities and scales in the decaying region. This work is listed in my references.

Regarding the other point that flocculation increases with increasing turbulence, papermakers are, of course, looking at flocculation downstream from turbulence in a headbox. It is my belief that the decaying turbulence is the means by which flocs are created. If you have a very high turbulence that is decaying, you may form very intense transient flocs which move into a zone of low shear and thereafter persist as coherent flocs. This flocculation has a "grainy" appearance which is the poorer formation I believe you are referring to.

Ebeling Have you observed in your studies as a function of the fibre type, flexibility, length and the decaying time available, that there are some critical intensity scale limits for the turbulence which takes you into the "grainy" structure that you described?

Kerekes You must achieve a critical level of turbulence intensity in the turbulent zone to break up flocs. If this is not achieved, you simply have flocs moving around. Beyond this, we have no information on critical limits for flocculation including creation of the "grainy" flocculation.

Kallmes If you look at the reformation of flocs in the flow from a high-turbulence headbox you can see that within a few centimetres of the slice the flocs reform. The reflocculation time is of the order 10-12 milliseconds.

Kerekes In Table 1 of our paper we have listed the various reflocculation times that have been published in the literature. The times are, as you can see, very short indeed.