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A CONCEPT FOR FIBRE FLOCCULATION IN TURBULENT FLOW

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ABSTRACT

A concept for the fibre flocculation process in turbulent flow is presented including both rupture and aggregation of fibre flocs. Based on results from the literature, a mechanism is proposed for the breaking-up and the building-up of flocs in interaction with turbulent eddies of different length scales in the turbulence spectrum. The mechanism has been formalized into a two-way hierachical concept with analogy to the decay of a scalar fluctuation.

Deformation and break-up of flocs by turbulent eddies with a length scale similar to the floc scale dominates the rupture process. Eddies of a smaller scale agitate the floc causing weakening and activation of the network. Floc aggregation happens due to floc collisions when the flocs are transported by turbulent eddies of a larger scale. The smaller scales activate the floc surface, and increase the probability of forming a floc. Erosion and deposition of single fibres takes place in the turbulent fine structure.

This concept finds support when tested and compared with the results in the literature. Experiments have been conducted in a vertical pipe flow with a varying flow rate, fibre length and consistency, taking measurements at various positions downstream of an orifice. Results were obtained using high speed movie film, image analysis of still photos and

measurements of flocculation and turbulence spectra using a laser. Increasing the turbulent kinetic energy or decreasing the macro scale gives lower floc intensity at large length scales.

INTRODUCTION

Dispersion of fibre flocs is an important part of the paperforming process and is critical for making a sheet with good formation. There has been extensive research in this area in the last 40 years, and excellent reviews have been published by Parker (1), Norman et al. (2), Kerekes et al. (3) and Soszynski (4). The purpose of this paper is to discuss the mechanical flocculation process, leaving out other aspects of flocculation. This includes the mechanism for both rupture and aggregation of flocs. We will propose a concept for the flocculation process at low consistencies ($c<2\%$) which may further be developed into a quantitative model. Flocculation in unit operations in papermaking can then be simulated in a numerical model.

Mechanical flocculation is defined by Mason (5) as the mechanical entanglement of fibres by forced collisions in shear flow. Mason (6) showed that the shear motion caused both aggregation and rupture of flocs. He defined a dynamic equilibrium as a state where fibre flocs continuously form and disperse. The equilibrium will shift in the direction of higher dispersion with increasing shear rate. Experiments supporting this have been reported by Mason (7).

Robertson and Mason (8) have discussed the various flow regimes in pulp suspensions. In the turbulent regime they concluded that pulp flocculation tended to be in a state of dynamic equilibrium. They proposed that the scale of turbulence was related to the degree of flocculation, and the presence of flocs inhibited the development of small scale turbulence. Parker (9) concluded, for a turbulent fibre suspension, that the better fibre dispersion, the finer is the scale of turbulence. Hence, the turbulence will decay faster, and reflocculation will occur more rapidly.

Meyer and Wahren (10) developed a model for the strength of fibre networks. If a fibre suspension is agitated, the fibres will twist and bend. When the agitation ceases, the fibres will try to obtain their original shape. A fraction of the fibres will lock in strained positions in a network if they are restricted due to the presence of other fibres. The network strength is then a function of the normal and frictional forces transmitted in the contact points between fibres. This mechanism is also present in the flocculation process. As postulated in a model by Anderson (11), to break a floc one has to apply a force greater than the internal strength of the floc. The probability of rupture of fibre flocs is the product of the probability of the occurence of a certain fluid stress and the probability that the strength of the floc is lower than this stress. Results from experiments indicate agreement with this theory.

Parker et al. (12) concluded that the effective turbulent eddies in the rupture process are those of a scale approximating the floc scale. d'Incau (13) stated that turbulent length scale, kinetic energy and strain rate are all important variables in the floc dispersion process. However, the lifetime of the effective eddies must be longer than the suspension's response time.

A consequence of Anderson's model (11) is that flocs may travel for a long distance without breaking-up. This effect was observed, and one may ask whether a true dynamic equilibrium exists in turbulent flow. Kerekes (14) made the same observations in decaying turbulence downstream of a grid. When the turbulent energy was high, formation and rupture of transient flocs was observed. Further downstream the turbulent energy decayed and the transient flocs turned into static, stable flocs.

The dispersion and aggregation process have been studied seperately. Lee and Broadkey (15) studied the rupture of single flocs in a steady shear field at various shear rates. The break-up process started as a global phenomena including deformation, stretching, breaking and fragmentation and depended strongly on the applied shear rate. It was followed by a local erosion process of surface fibres. This process was slower, and the rate of size reduction decreased as the floc became smaller. The effective turbulent scales in the global break-up process were those comparable to the floc size, while small scale turbulence was effective in the erosion process. Soszynski (4) studied the formation of strong coherent flocs by elastic interlocking of fibres using a partly filled rotating cylinder. Above a certain threshold in consistency, flocs formed due to fibre crowding in the deceleration zone. The newly formed flocs were strong enough to persist the high shear zone and became densified when going through the deceleration zone again.

Parallels to the floc rupture process can be found in the break-up of drops (16) and polymer flocs (17, 18) in turbulent flow. Hinze (16) proposed that break-up was likely when the dynamic pressure was greater than the surface stress of the drop. The dynamic pressure is caused by changes in velocity over distances equal to the drop diameter and is a function of the fluctating velocity. Tomi and Bagster (17) used the same concept as Hinze (16) and gave expressions for break-up stress according to various scales in the turbulent spectrum. Hsu and Glasgow (18) applied a similar theory that floc rupture is likely when dynamic pressure is greater than the yield stress of the floc. They introduced a hierachical model where the break-up of flocs at one scale increased the numbers of flocs on the next smaller level.

A theoretical approach was presented by Hourani (19, 20) where the floc size distribution was predicted from the turbulent energy spectrum in two-phase flow. The model was based on the concept of dynamic equilibrium and assumed that the floc size was equal to the turbulent eddy size. The weight fraction of flocs at various scales was calculated from the free energy of formation using the mass-action law. This model was verified with experiments (20).

Although the research in this area is extensive, there exists no complete theory for the flocculation process in a turbulent flow. We have synthesized the results in the literature and proposed a concept for the flocculation process. To further support the concept we have studied flocculation in a vertical pipe flow downstream of an orifice using high speed photography and image analysis of still photos. Flocculation and turbulence spectra have been recorded in a position near the wall using a laser. Data was taken at two positions downstream of the inlet ($z/D=2$, 20) with two bulk velocities ($u_b=1$, 3 m/s) and two fibre types (softwood, hardwood) at two consistencies ($c=0.17$, 0.67%).

THEORETICAL CONCEPTS

Turbulence

Turbulence is a time dependent motion described as a three dimensional vortex structure with eddies characterized by a velocity (u') and a length (l') scale. The theory of turbulence has been explained in detail by Hinze (21) and Tennekes and Lumley (22). The turbulent energy spectrum is defined as the Fourier transform of the autocorrelation coefficient of velocity and represents the turbulent kinetic energy associated with different wavenumbers (k) ($k=2\pi/l'$).

Turbulent kinetic energy is extracted from the mean flow field at large length scales and dissipated into heat by viscous forces at the small scales. Energy is cascaded down the scale hierarchy by a vortex stretching mechanism where the angular momentum of the vortices is conserved. Vortex stretching involves exchange of energy because the turbulent strain rate performs deformation work on the vortices which are being stretched.

We can define a macro scale (L') for the large energy containing eddies and a Kolmogorov micro scale (η) for the small dissipative eddies in turbulence. If we have the scales u'_n, l'_n at a specific scale level (n) in the energy cascade, the production (P) and dissipation (ε) of turbulent energy at this level can be expressed as (ν: kinematic viscosity):

$$P_n \sim u'_{n-1} \,/\, l'_{n-1} \cdot u'^2_n \tag{1}$$

$$\varepsilon_n \sim \nu \cdot (u'_n \,/\, l'_n)^2 \tag{2}$$

An illustration of the energy transfer is shown in fig. 1.

The dissipative eddies are concentrated in narrow regions in the high shear zone between large eddies. These fine structures are believed to be vortex tubes, sheets or slabs whose dimensions are of the same magnitude as the Kolmogorov micro scale. Dissipation is therefore characterized as an intermittent process since the regions of fine structure only cover a small fraction of the total volume.

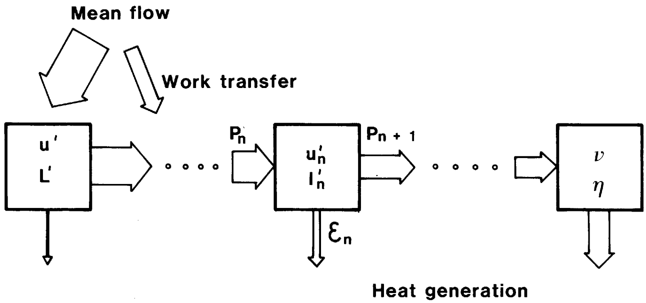

Fig.1: The turbulent energy cascade.

Fibre flocculation concept

A fibre floc will cause a local fluctuation in consistency (c'^2) and has a defined length scale (l'). A power spectrum of the flocculation index $(c'/\bar{c})^2$ is obtained by taking a Fourier transform of the autocovariance function (23). It describes the distribution of floc intensity over various length scales. The flocculation process is linked to the turbulence mechanisms and has analogies to turbulence, both being described by an intensity (c', u') and a length scale (l'). The following concept is proposed assuming that the basic mechanism in the turbulent energy cascade is valid.

The large turbulent eddies will contain local fibre networks while the smallest eddies contain only single fibres or will be free of fibres. During the turbulent stretching of large eddies, their internal network is deformed. Break-up is probable if the deformation forces are larger than the internal network strength. The length scale of the straining vortices will be of the same order as the floc scale, while eddies of a smaller scale will agitate the outer part of the floc making the floc weaker and rupturing more probable.

Flocs at one length scale can be transported by turbulent eddies of larger scales, and floc collisions will occur. Turbulent eddies of smaller scales will activate the outer part of the floc. We can define a turbulent time scale (t') as $t'=l'/u'$, such that larger eddies have a longer time scale than smaller eddies. Collisions between flocs will cause build-up when the contact time is long enough for the local floc network to settle.

While the turbulent energy cascade has a dominant energy flux down the scales, flocculation is a two-way process. For flocs of a large scale, we will have deformation by turbulent eddies with high energy and activation by a set of smaller eddies. Hence, at large floc scales the break-up process is favourable. Small flocs will be transported by a set of larger eddies combined with intense network activation by smaller eddies. The build-up process is therefore dominant at smaller floc scales. This indicates the existence of an equilibrium length scale (l'_e) where both break-up and build-up have the same probability. The equilibrium length scale is a function of fibre properties and the local turbulence structure.

The regions of turbulent fine structures are located in the high shear zone between flocs / eddies. This causes erosion and deposition of single fibres and is independent of the large scale aggregation and rupture mechanism. The erosion process activates single fibres, and deposition takes place when the energy dissipates.

The described process can be formalized into a flocculation concept. From Tennekes and Lumley (22) we have general expressions for production (P') and dissipation (ε') of a scalar fluctuation:

$$P' \sim O(c'^2 \cdot u' / l') \tag{3}$$

$$\varepsilon' \sim O(c'^2 / l'^2) \tag{4}$$

The scalar energy cascade is mainly a one-way process where adjacent scalar eddies interact. Flocculation is a two-way process which involves turbulent eddies from the whole spectrum. We therefore propose the following modified expressions for production from break-up (P1) and build-up (P2) and the erosion process (E) at one scale level (n) (α: weight function):

$$P1_n \sim c'_{n-1} / l'_{n-1} \cdot \sum_{i=n}^{\infty} \alpha_i u'_i c'_i \tag{5}$$

$$P2_n \sim c'_{n+1} / l'_{n+1} \cdot \sum_{i=1}^{n} \alpha_i u'_i c'_i \tag{6}$$

$$E_n \sim (c'_n / l'_n)^2 \tag{7}$$

An illustration of the flocculation process is shown in fig. 2.

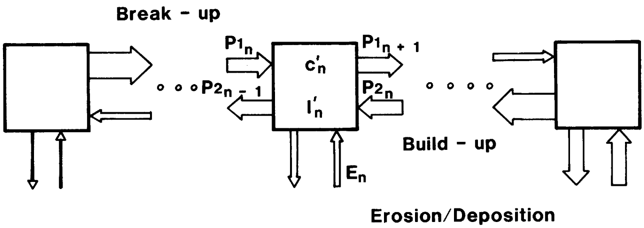

Fig.2: The fibre flocculation concept.

Fig. 2 indicates a rupture and aggregation process which is an analogy to the turbulent energy cascade. In the energy cascade, mainly eddies of adjacent scales interact. However, in the flocculation process all turbulent eddies smaller than the floc size are active in the break-up process, and all eddies larger than the floc sizes contribute to build-up.

EXPERIMENTAL STUDY

The flocculation process was studied in a vertical pipe flow downstream of an orifice. The pipe diameter (D) was 23.8 mm and the orifice had a 64% open area. Observations and measurements were made at two positions (z) downstream of the orifice; z/D=2 and 20. Two flow rates were studied with bulk velocities (u_b) of 1 and 3 m/s. Bleached kraft pulp of both hardwood and softwood fibres were used, and their fibre length distributions (fig. 3) were measured by a Kajaani FS-100. Experiments were run at two consistencies (c); c=0.17 and 0.67%. The fibres were dyed with a blue colour for the visual studies.

A Hycam high speed movie film camera was used to visually study the flocculation process. A light source was mounted behind the pipe, and the film was taken with this transmitted light at 10,000 frames/second at c=0.17%. The flow moved $\Delta z \sim 0.3$ mm (Δz : spatial resolution) in each frame at the highest flowrate. The film was taken at two positions: $2<z/D<6$ and $16<z/D<20$.

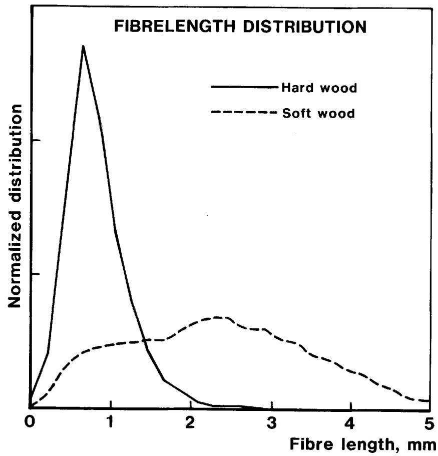

Fig.3: Normalized length distribution for softwood and hardwood fibres.

By using a flash light behind the pipe, still photos of floc structure were taken in transmitted light. The flash light gave a short light pulse (Δt=65 μsec) and the photos showed good sharpness (Δz<0.2 mm) at both flowrates. The photo was later digitized with 8 bits resolution (256 grey levels), and the various grey levels give a value for the local fibre concentration. The digitized signal was analyzed using Fast Fourier Transform (FFT) to get the spectral distribution of flocculation intensity (23). By analysing 25 mm on each side (~D) of the actual z-position and using a 256 point FFT in the z-direction, a reproducible spectrum was obtained with wavelengths (l') in the range 0.4–10 mm. Spectra at larger wavelengths could be recorded using a longer intervall (>2D), but the result would be less representative for the actual z-position. Results were generated for a wall (0.04<y/D<0.27) and a center (0.77<y/D<1.0) region (y: distance from the wall).

Ek et al. (24) have developed a method to measure flocculation spectra using a laser. When the intersection of two laser beams was focused on a position near the wall, the intensity of reflected light was a linear function of the local fibre concentration. A photomultiplier converted the reflected light to an analog voltage signal. The floc spectrum was obtained by doing an FFT of the fluctuating part of the signal (c'). Spectra were recorded at a y-position equal 2.5 mm from the wall (y/D=0.2). Laser Doppler Anemometry (LDA) was used to measure the local velocity (u) in the same position. Turbulence spectra can be recorded by doing a FFT on the fluctuating velocity (u') signal. Data was taken both in pure water and fibre suspensions. The latter results should be treated with caution since the fibres caused noise in the recorded signal.

RESULTS

Results from the three experimental techniques used in this study are presented to indicate support for the flocculation concept. Pictures from the high speed movie film showing the floc rupture and aggregation process are presented in fig. 4. The flow time (t) in milliseconds is measured between subsequent frames. Just downstream of the inlet ($2<z/D<6$, fig. 4a, 4b), the fibre suspension is in a state of dynamic equilibrium (6). The rupture and aggregation process is faster at the higher flowrate (fig. 4b), and the suspension is visually more dispersed. Further downstream ($16<z/D<20$, fig. 4c, 4d) the film shows a more static situation with small changes in floc structure. Only at the highest flow rate can some floc rupture and aggregation be observed. These observations are similar to results obtained by Kerekes (14) in decaying turbulence.

Still photos of flocculation are presented in fig. 5, and these were analysed by using a image analyser. The flocculation spectra represent the wall (no.1) and center (no.2) region in the pipe. Fig. 6 shows the flocculation spectra in the two regions at two different downstream positions for softwood fibres at u_b=1 m/s. There is a higher floc intensity at larger wavelengths in the center compared to the wall region, and this effect is more pronounced at z/D=20. The same effects are observed at the higher flowrate (u_b=3 m/s, fig. 7), but with a smaller magnitude. The floc structure in the wall region is similar at the two z-positions. Flocculation spectra for hardwood fibres at u_b=3 m/s are presented in fig. 8. There is a lower intensity at larger length scales compared to softwood fibres (fig. 7), and the floc structure in the wall region is similar to the center region. The presented results can be visually confirmed by looking at the photos in fig. 5.

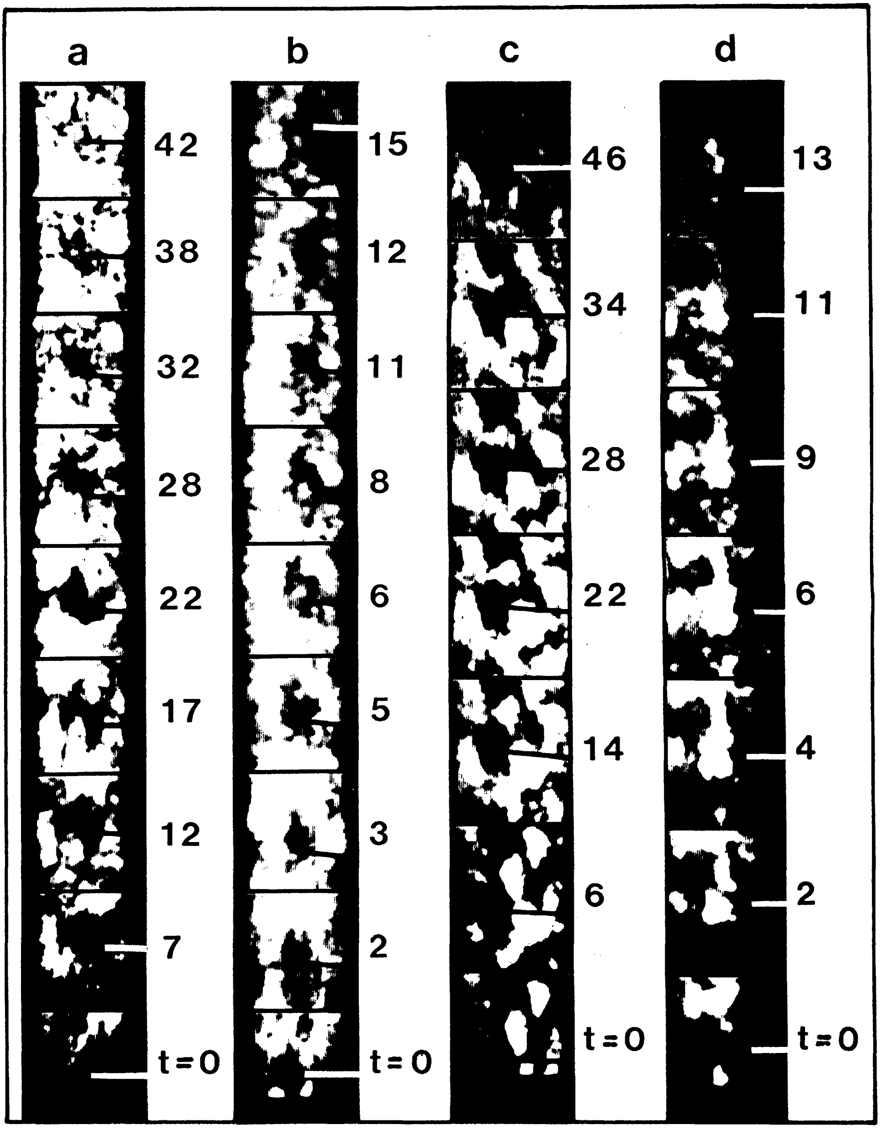

Fig.4: High speed movie, softwood fibres, c=0.17%, time in msec.
a: u_b=1 m/s, z/D= 2- 6 b: u_b=3 m/s, z/D= 2- 6
c: u_b=1 m/s, z/D=16-20 d: u_b=3 m/s, z/D=16-20

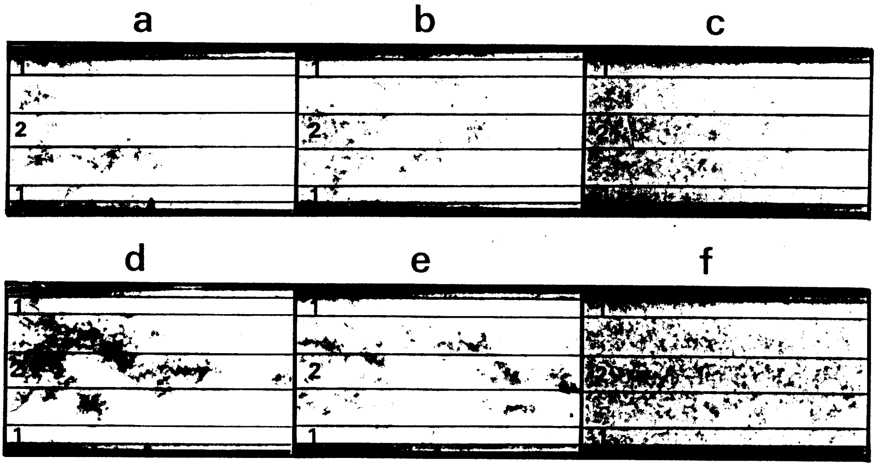

Fig.5: Still photos, softwood (SW) and hardwood (HW) fibres, c=0.17%

a: u_b=1 m/s, z/D= 2, SW b: u_b=3 m/s, z/D= 2, SW
c: u_b=3 m/s, z/D= 2, HW d: u_b=1 m/s, z/D=20, SW
e: u_b=3 m/s, z/D=20, SW f: u_b=3 m/s, z/D=20, HW

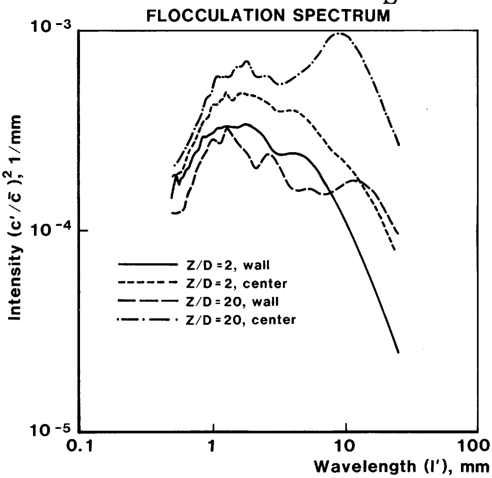

Fig.6: Flocculation spectra, softwood fibres, c=0.17%, u_b=1 m/s

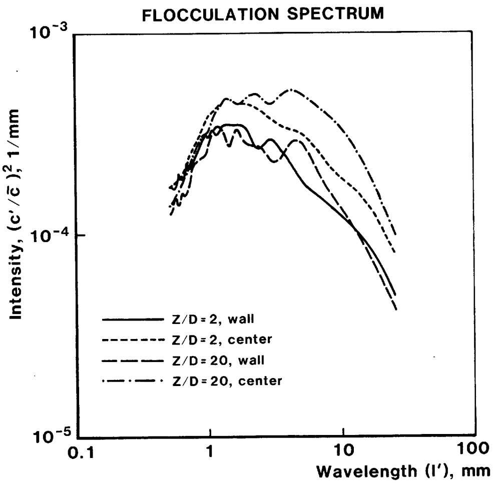

Fig.7: Flocculation spectra, softwood fibres, c=0.17%, u_b=3 m/s

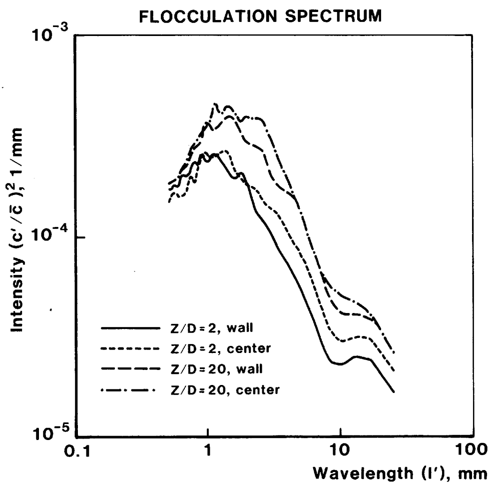

Fig.8: Flocculation spectra, hardwood fibres, c=0.17%, u_b=3 m/s

The flocculation spectra obtained using the laser system have been integrated for 0.3<l'<50 mm and presented as a accumulated characteristic curve of the flocculation index (23). Due to different amplification factors in the various experiments, the curves have been made non-dimensional by dividing with the total energy ($c\ell^2$). Hence, the curves show only floc scale information and should be compared relatively to each other. Fig. 9 presents characteristic index curves for softwood fibres at c=0.17% at two different bulk velocities and downstream positions. Increased bulk velocity gives a relative lower intensity at larger wavelengths. The relative higher floc intensity at small scales with z/D=20 compared to z/D=2, can be explained by a lower local consistency in the region near the wall at z/d=20 (fig. 5). This effect is less pronounced for hardwood fibres (fig. 10) at u_b=3 m/s. The characteristic curves for hardwood fibres also show a relative low intensity at large scale compared to softwood fibres. The effect on flocculation of the concentration of softwood fibres at u_b=3 m/s is presented in fig. 11. By comparing the results at the same downstream position, one observes at higher consistency a relative higher floc intensity at larger scale. These results compare qualitatively well with those of Nerelius et al. (25).

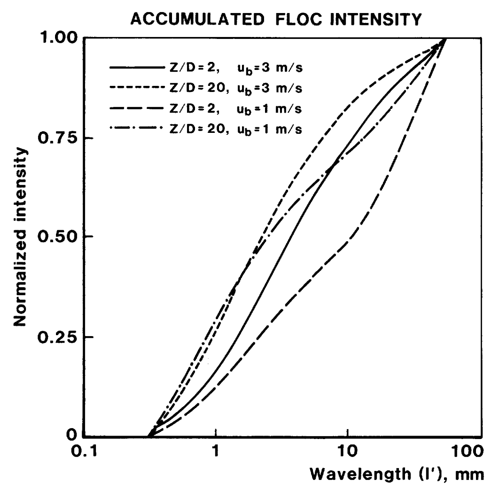

Fig.9: Accumulated floc intensity, softwood fibres, c=0.17%

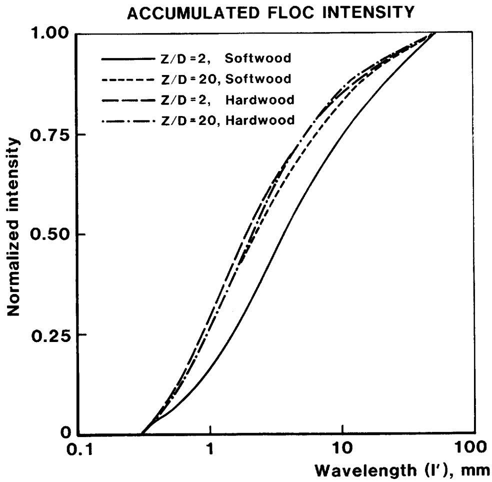

Fig.10: Accumulated floc intensity, c=0.17%, u_b=3 m/s

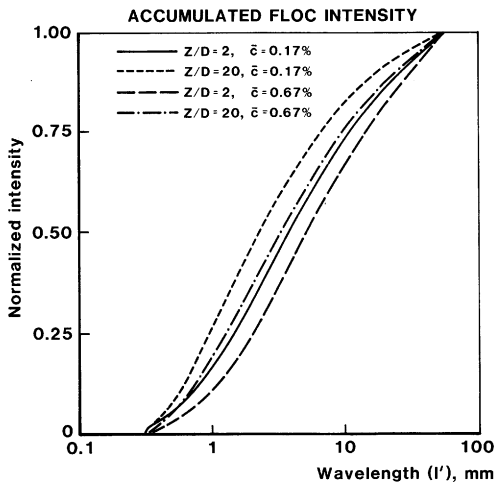

Fig.11: Accumulated floc intensity, softwood fibres, u_b=3 m/s

LDA readings taken in fibre suspensions are noisy and give low sampling rate of valid signals. This causes problems when trying to obtain reliable turbulence spectra at high frequencies. The results are therefore only presented as turbulent velocity (u′) and macro length scale (L′) (tab. 1). The macro scale increases with bulk velocity and fibre consistency. The high turbulent velocities at u_b=1 m/s and z/D=20 in this flow loop have been discussed by Steen (26). It is believed to originate from a Karman vortex street created by the orifice in the inlet. The same effect can be observed for pure water (fig. 12) with turbulent energy concentrated at small length scales. Although the turbulent structure is modified in the presence of fibres (26), the results are included to present the changes in turbulent structure at different bulk velocities and positions downstream. The high turbulent energy at large scale for z/D=2 is probably caused by the recirculation zone after the orifice (26).

z/D	u_b (m/s)	c (%)	u′ (m/s)	L′ (mm)
20	1	0.17	0.31	2.9
20	3	0.17	0.33	13.3
20	1	0.67	0.30	3.0
20	3	0.67	0.33	23.1
20	1	0.0	0.18	5.9
20	3	0.0	0.25	16.1
2	1	0.0	0.35	13.1
2	3	0.0	0.58	47.7

Table 1 : Fluctuating velocity (u′) and macro length scale (L′) at various positions (z/D), bulk velocities (u_b) and consistencies (c) of softwood fibres.

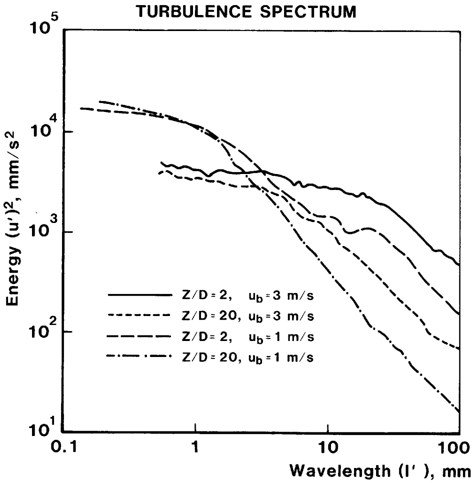

Fig.12: Turbulence spectra in pure water.

DISCUSSION

Rupture and aggregation mechanism

The rupture process consists of large scale deformation and break-up by the turbulent eddies, and a local small scale erosion process. This follows closely the observations of Lee and Broadkey (15). Also Kerekes et al. (3) reported rupture of flocs in the large turbulent strain rate between two vortices. During the aggregation process both activation by small scale eddies and floc collisions caused by the larger eddies is important for the formation of flocs. A similar effect was presented by Soszynski (4) from experiments in rotational acceleration / deceleration flow forming strong coherent flocs.

Small scale activation of fibres followed by fibres locking in a network, is the foundation of Meyer and Wahren's (10) model for network strength. We propose that the same mechanism is also valid for single flocs. Floc break-up is likely if the applied turbulent stress is greater than this internal strength (11) and is active for a sufficiently long time (13). This is typical for large energy containing eddies. Since the turbulent eddy scale should be close to the floc scale (12), break-up of large flocs is more probable than rupture of small flocs. The deformation energy needed will be extracted from the turbulent kinetic energy causing an extra dissipation of energy.

Kerekes' (14) discussion of Mason's (6) dynamic equilibrium finds support in the presented concept. In decaying turbulence, transient flocs in dynamic equilibrium turned into stable, static flocs. The flocculation process is trying to reach a local equilibrium between flocculation and turbulence structure. In decaying turbulence, the rate of decay will increase with increasing wavenumber (21), and the flocculation structure will try to obtain equilibrium with the changing turbulence structure. With less turbulent energy at small scale and still having large eddies, the flocs will tend to grow.

The high speed movie film confirmes the above described mechanisms in decaying turbulence. Just downstream of the orifice (fig. 4a, 4b) we observe continuous rupture and aggregation of flocs. This indicates that we have a higher energy than the threshold energy for the breaking up of flocs at all scales. The turbulent energy is higher at u_b=3 m/s than u_b=1 m/s, and the result is that the time scale in the flocculation process is shorter. Further downstream (fig. 4c, 4d) the energy has decayed giving a more static flocculation structure.

Hierachical floc structure

Hsu and Glasgow's (18) hierachical model resulted in a set of balancing equations, one for each scale level. They only considered rupture of flocs, and the model does not admit the possibility for growth of fragments or flocs. This latter does happen, and a more complete process must be described by a two-way mechanism, both rupture and aggregation. However, Hsu and Glasgow's (18) approach supports that the flocculation process takes place in a set of scale levels.

The one-way model is an analogy to the decay of a scalar fluctuation (22). The scalar gradient associated with an eddy at one scale is distorted by the velocity fluctuation at the next smaller scale. This is a continuous process where adjacent scales interact, and the scalar decay process runs in parallel with the decay of turbulent eddies. An analogy to the two-way flocculation concept is present, but with some major differences. First, it is doubtful whether the fibre flocs follow the continuum approximation (27) because of their large dimensions. Second, turbulent eddies both larger and smaller than the floc scale contribute in the flocculation process.

The cascade model for a scalar fluctuation describes the decay of the fluctuation (ϕ'^2) as the eddy length scale is reduced. Is the flocculation concept only a length scale model or also a decay / production of fluctuations (c'^2) ? If a floc was torn apart, we would expect to have the same fluctuation, just at smaller length scale. Collision between two flocs would give the same fluctuation at a larger length scale. This would indicate that the concept is just a scale model. However, the flocculation process is different. During the deformation and rupture of flocs, turbulent eddies of smaller scales act on the floc making it less dense. Hence, a length scale reduction causes the forming of flocs with lower intensity (c'). Under the aggregation process, floc collisions make the flocs more dense (4), and the intensity increases. We therefore conclude that the proposed concept includes production / decay of both the fluctuation (c'^2) and length scale (l').

Flocculation and turbulence

The interaction effect between turbulence and flocculation can be discussed based on the presented results. Increasing the flow rate means increasing the turbulent energy, and we should have more energy to break flocs at smaller scale. The result is lower floc intensity at large scale, and this can be observed in all the presented results. Increasing the concentration (fig. 11) has the opposite effect since we would expect a lower turbulent kinetic energy and a higher floc strength (28). It also gives a higher crowding factor (n_f) (3), making floc collisions and build-up more likely.

$$n_f = 2/3 \cdot c \cdot (l/d)^2 \qquad (8)$$

Here l is the fibre length and d the fibre diameter. A shorter fibre length results in a lower crowding factor, and the turbulent kinetic energy will be higher compared to a suspension with longer fibres (26). We should therefore have more energy at a smaller scale giving a lower floc intensity at larger scale (fig. 8, 10). The strength of the fibre network formed from shorter fibres is also lower, making rupture easier (28).

We observe a higher floc intensity at larger scales in the center compared to the wall region for softwood fibres (fig. 6, 7). This can be explained by the turbulent energy which will be lower in the center than closer to the wall in pipe flow. The turbulent length scale is smaller in the wall region. Analogue effects can be observed at the downstream position (z/D=20). In decaying turbulence (fig. 6 - 8) we also observe a higher floc intensity at larger scales. The laser measurements (fig. 9, 11) indicate the opposite; a reduced floc intensity at larger scales for z/D=20. However, this is measured close to the wall, and from the still photos (fig. 5) we observe a local lower consistency in this region at z/D=20 compared to z/D=2.

Turbulent eddies of similar scales as the flocs will be effective in the rupture process (12), and to disrupt flocs at small scales we need small scale turbulence (9). Wahren (29) reported that a fluctuating strain would cause fatigue softening of the fibre network, and the fine structure regions between larger eddies may play a role in weakening the flocs. This is supported by the concept. A spectral distribution of turbulent energy is necessary to produce small scale floc structure since break-up at one scale produces flocs at a smaller scale. The macro scale of turbulence (L') should be small, and the energy should be concentrated at smaller scales. A small Kolmogorov scale (η) would therefore indicate good floc dispersion. From Tennekees and Lumley (22) we have (Re_t: turbulent Reynolds number):

$$\eta / L' \sim Re_t^{-3/4} \qquad (9)$$

The macro scale (L') is related to the geometrical flow dimensions. The equation (9) implies that increasing the turbulent energy, or decreasing the macro scale both will reduce the Kolmogorov micro scale. Both principles have been used in the design of headboxes to obtain a good floc dispersion. A lower macro scale will cause a lower floc intensity at large length scale (tab. 1, fig. 9, 11) (13). Although the turbulence spectra presented in fig. 12 are from pure water, they indicate the relative differences in structure at the two positions and flow rates. The higher floc intensity at large scales close to the wall at z/D=2 compared z/D=20 (fig. 9) can be explained by the turbulent energy being concentrated at a larger scale.

The proposed concept indicates that while break-up is more probable at large floc scales, build-up is more likely at small scale. Therefore, we could define, analogous to Mason (6), a local equilibrium scale (l'_e) where both rupture and aggregation have the same probability. However, the flocculation process is different from Mason's dynamic equilibrium (6), and the equilibrium length scale depends on the local turbulence structure. By increasing the turbulent energy or reducing the macro scale, the equilibrium floc scale should be smaller. Wågberg and Lindstrøm (30) have defined a length scale l'_{50}, as the wavelength where we have 50 % of the accumulated floc intensity. The discussion indicates that l'_e should be proportional to l'_{50}.

The rupture mechanism is related to the turbulent energy cascading down the scales. A large turbulent energy flux should give a smaller equilibrium floc scale. The total dissipation must be equal to the large scale energy flux (u'^3/L'). Wahren (31) has postulated that a larger power dissipation is needed to achieve a dynamic equilibrium (6) at a higher consistency. This indicates that a large energy flux is necessary to break up flocs at high consistency.

CONCLUSION

A concept for fibre floc rupture and aggregation has been discussed. The flocculation process interacts closely with the turbulent energy cascade. Eddies smaller than the floc size will weaken the floc and activate the network. Eddies with a length scale larger than the floc scale will promote floc build-up, while eddies of a similar scale to the floc contribute to rupture of flocs. Erosion and deposition of single fibres will take place in the dissipative fine structure regions. At large scales rupture of flocs is more likely than aggregation, while at small scale the build-up process is more probable.

The described mechanism has been formalized into a hierachical concept with analogy to the decay of a scalar fluctuation. However, the concept is a two-way hierachy including both floc rupture and aggregation where eddy scales, both larger and smaller than a certain floc size, are active in the flocculation process. The concept finds support when tested against observations from the literature. Experiments have been conducted in a vertical pipe flow, and results using high speed movie film, image analysis of still photos and laser measurement indicate that the proposed concept is reasonable.

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Transcription of Discussion

A CONCEPT FOR FIBRE FLOCCULATION IN TURBULENT FLOW

M. Steen

Prof. F. Onabe, University of Tokyo

Considering the actual papermaking system, your experimental system and mathematical formulations look very much simplified. Although flow conditions seem rigidly formulated mathematically, what is the assumtion you have made about fibres. Do you consider them rigid or compressible bodies and flexible bodies?

M. Steen

The fibres are of a certain length, and can have certain flexibilities. These must be taken into account in such a model. Of course these will interact with the constants I just described.

A. Ibrahim, PAPYRUS

I am trying to relate your numbers to the practical world of papermaking. If you consider the consistency, you selected a figure of 0.17 for softwood. Taking the concept of Wahren, the softwood consistency, taking into account an aspect ratio of 100, comes to about 0.38 for an aspect ratio of 70, hardwood comes to about 0.6 - 0.7. You have been using a very low consistency and also the velocity of 1 and 3 metres per second, which you mentioned, is applicable to approach flow systems where we talk about for 3 metres/sec maybe 7 to 10 metres pipe diameter. In the distributor tubes, we talk about 10 metres per second. My question is why did you depart from the normal papermaking practices?

M. Steen

First, in the proceedings you will see that we have also worked at high consistency at 0.67%. The nice thing about having low consistencies is that you can take optical images from it, but we still believe that the described mechanisms are still valid. Never the less, calibration should be done at high consistency. Second, a comment on the velocities, the Reynold's Number in this case are still high even at 1 metre per second. We have also carried out turbulence experiments at much higher speeds and consistencies and this is due to be published in December in the Nordic Pulp and Paper Research Journal. You have to study things in a laboratory scale, but hopefully these can be related to full scale.

A. Ibrahim, PAPYRUS

In terms of the Reynold's Number, I do not know what the diameter of the pipe is, but it has to be very low compared to the practical papermaking. The Reynold's Number is **v** times **d** divided by the kinematic viscosity, therefore to satisfy a given Reynold's Number at a smaller diameter, you have to increase the velocity quite substantially. What I am saying is that the velocity is far lower than our current mill operation. One further comment is that these equations are not in the proceedings, how do I get them?

M. Steen

Our velocities are still high enough to create turbulent flow. As to the second comment, this work will be presented in a future report, but I felt it was worth presenting them to stimulate discussion.

Dr. J. Mardon, Omni Continental

There are two references you might wish to consult. (Ref.1) is the original work in England on the step diffuser on which Escher Wyss based their original invention, which explored the hydrodynamics of the step tube very extensively. (Ref. 2) is the work by Rolls Royce on flow downstream of the fully developed flow in tubes.

(1) A.K. Runchall & D.B. Spalding
Steady Turbulent Flow & Heat Transfer Downstream of a Sudden Enlargement in a Pipe of Circular Cross Section.
Warme Und Stoffübertragning 5 (1972) 31, 38.

(2) P.E. Roach of Rolls Royce Co.
The Generation of Nearly Isotropic Turbulence Downstream of Streamwise Tube Bundles.
Int.J. Heat & Fluid Flow 0142-727X/86/020117-09
Butterworth & Co. (Publishers) Ltd
1986 Pages 117-125.

M. Steen

There are also references to work with the step diffuser and calculations from this in 1988 TAPPI Engineering Conference.

Prof. C.T.J. Dodson, University of Toronto

As I understand it, you have a new model for turbulence and flocculation. In the situation in which you did this, there is a strong coupling which is intensified at the critical length scale. In my understanding, this is the first time that such a co-operative process has been formulated in this way. I would also like to see the derivation of those equations, and I would be happy to have a preprint. To what extent do you rely on the classical work of Kolmogorov and at what stage does your new input of the flocculation geometric structure occur.

Prof. Bo Norman, Royal Institute of Technology, Sweden

Just a short comment about the two references mentioned. This is what review papers are for. If you look at my review, no. 47 is the one which J. Mardon mentioned as the first description of a step diffuser and the one you mentioned is no. 48 in my paper.

M. Steen

Your comments are correct. The assumptions as to whether you have Kolmogorov length scale may be queried. The formation and break up of each floc may also be a dissipation of turbulent energy as well, which means that your Kolmogorov length scale may not be so small as in one phase flow. Most of the dissipation is therefore probably caused by other factors in the flow. The reason for pulling in the Kolmogorov scale is that it is an interesting way of discussing the concept, but it is not altogether correct.

Dr. B.D. Jordan, PAPRICAN

You assumed that the turbulence in the water would be mimicked in the turbulence which you will see in the flocculation, and you give data for both. In your interpretation, do you feel that the spectra that you have given for the flocculation would actually fit this mimicking property, i.e. does this data support your model?

M. Steen

Yes, I do feel that they mimic it. There is a publication coming out soon (Nordic Pulp and Paper Research Journal) where we are using a refractive index technique to really measure turbulent spectra in a suspension of fibres of various lengths, and you will see there that spectra follow the same form as a pure fluid spectra. But to answer your question exactly, to see if flocculation spectra is mimicked by turbulence spectra, you need to do some more work. This could be done by coating single fibres with fluorescent particles, and by introducing a sheet of laser light, the fibres would emit fluorescent light, which you could collect at the same point that you measure turbulence spectra. However, currently, as you indicate, I just assumed that this mimicking property is present.