FIBRE FLOC FLOW

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Abstract
Flow phenomena in flocculated fibre suspensions have been investigated in plug, floc and turbulent flow regimes.

INTRODUCTION

Fibre flow in technical connections is normally a flow of fibre flocs. A floc is here a number of fibres, more or less stationary, kept together by cohesive forces. The investigated fibre suspensions are characterized by compressible flocs suspended in a low-viscous incompressible medium. Fibre networks are normally formed when internal floc motion ceases. Network properties and suspension rheology are therefore intimately related. Such a network consist of closely packed flocs, and the formation process normally makes the network very heterogeneous. The flocs may have an inner structure, being built up of smaller flocs, which in turn &c. The suspensions studied here are paper pulps[1], penicillin mashes[2,3,4], i.e. mould fibre suspensions, and synthetic fibre suspensions[1]. The results may have a wider applicability than for fibre suspensions.

RESULTS & DISCUSSIONS

1. Networks: The Cracking Rule

Water can easily be squeezed out of a normal pulp network, i.e. the Poisson ratio for the network is less than 0.5 and expansions perpendicular to compressions are insufficient to preserve the network volume. Consider an element consisting of a certain amount of fibres in a given volume of suspending medium. Since both components are incompressible, the total volume of an element remains constant. Let us compress such an element in one direction. The network elasticity makes the length decrease in the compressed direction the same for the network, but the Poisson ratio of the network creates a length deficit in perpendicular directions between element and network.

A cubic basin can be sheared into a rhomboid form. Partially filled with pulp to above the network formation concentration and slowly sheared to left or right, more or less parallel cracks open up in diagonal directions. If the cube is sheared back to its initial state the cracks close. If the shearing is continued in the opposite direction, new cracks open up, roughly perpendicular to the previous ones. The sequence is everywhere reversible with the same result, Figure 1.

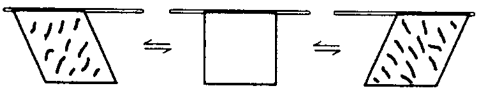

Figure 1. Principal result of the network cracking experiment.

Crack directions for different finite shearing angles were measured on photographs. Within the standard deviation, the average direction coincided with the compressive principal direction. This is the *cracking rule*. Due to the system heterogeneity, the cracks have a natural tendency to follow weak zones, i.e. winding paths between the flocs.

The free surface of the sheared network reveals that the inner pressure has pushed up flocs in winding ridges, Figure 2, the ridges being formed by chains of compressed flocs. The cracks are located in the grooves.

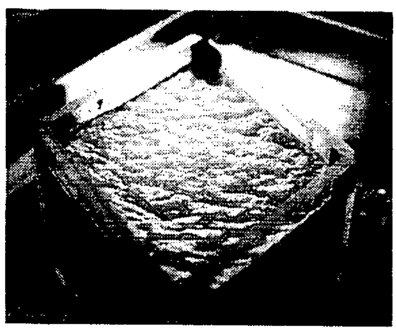

Figure 2. The network cracking experiment. Paper pulp 3.5%. Cube sheared right. Cube side 10 cm.

How can stress chains evolve in these systems? The over-simplified example in Figure 3 shows how the closest neighbouring flocs (1, 2 and 6) in *cooperative action* may effectuate this. The central floc is pushed in the positive x-direction while being free to move in the y-direction. Up to the *pitchfork bifurcation* at $x \approx 0.658$, the resistance to com-

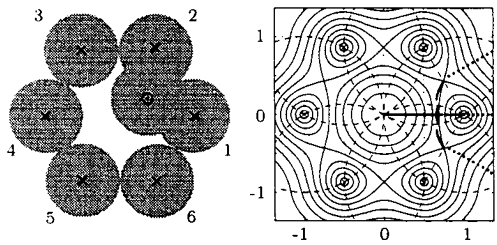

Figure 3. A stress chain formation mechanism. a) A movable elastic floc surrounded by six similar fixed flocs. b) System potential curves and stability curves.

pression of flocs nos. 6 and 2 overshadows the resistance of floc 1.

Figure 4 gives further examples of observed cracking patterns. The deformation of the marked squares and the application of the cracking rule explain the results. Oblique views reveal corrugated surfaces similar to those in Figure 2. The channel flow result can also be interpreted as an axial section through a circular tube. The tangential pattern often observed in the free surface of settling systems is a result of axial shearing of the compacting plug. In the free surface of mixed tanks, transition from Figure 4b to 4c is often observed when the impeller down-draught sets in. For fully cracked-through Couette plugs, axial extension of the crack tips at the cup gives the normally observed vertical axial cracking pattern. For somewhat lower concentrations, the axial spiral pattern in Figure 5a is also common. This is a result of axial torsion of the network cylinder by tangential shearing stresses over the bob/plug wall layer.

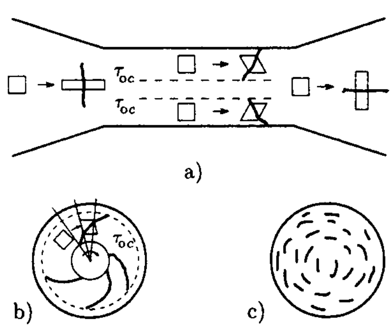

Figure 4. Network cracking patterns. Views from above. τ_{0c} cracking strength. a) Channel plug flow. b) Couette plug flow. c) Sedimentation.

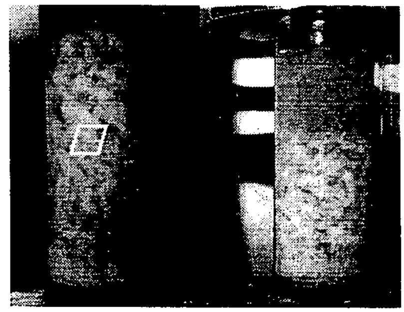

Figure 5. a) Axial spiral network cracking pattern. b) Floc splitting, 1% pulp, bob speed +400 rpm, cup speed −400 rpm. Cup outer diameter 15 cm.

2. Floc Flow: Splitting & Sizing

THEORY

The flow mechanisms are separated into *floc splitting* and *floc sizing*. Splitting creates new flocs out of old and obeys *the scaling law*. Sizing changes the magnitude (but not the shape) of already existing flocs. Sizing includes *synerism* (bulk and surface), *surface erosion* and other phenomena not covered by splitting. Splitting and sizing may act simultaneously, but splitting logically precedes sizing. *Module suspension* is an *ad hoc* model based on the splitting of abstract flocs, *modules*, Figure 6.

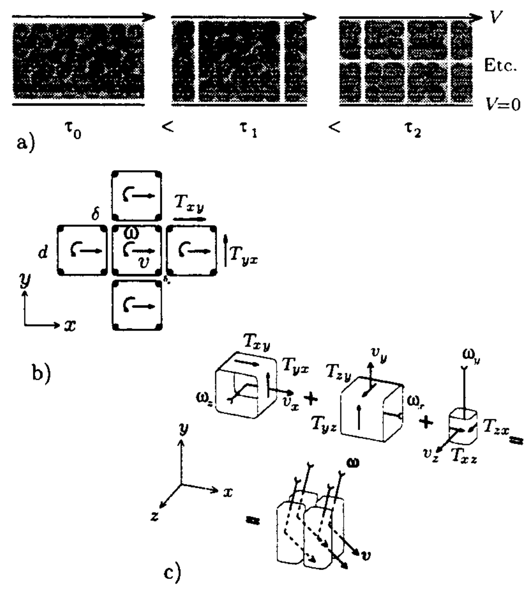

Figure 6. a) The plane splitting scheme, b) Plane module dynamics, c) Three-dimensional extension.

This model introduces the collective aspects at the outset. Its equations can be solved algebraically. Splitting criteria and sizing functions may be introduced independently. Subsequent semi-empirical work may therefore commence from a uncomplicated set of equations. The model predicts e.g. increased energy dissipation due to splitting and decreased dissipation due to sizing.

EXPERIMENTAL EVIDENCE

i) Splitting; Superimposed upon the main tangential shearing field in a cylinder viscometer is a smaller axial field caused by the end effects. At speeds such that the combined stress field exceeds the floc strength in the viscometer gap, a fairly sharp transition can be created, Figure 5b. Measurements on this photograph give an average floc diameter ratio of 2.05 ± 0.5.

ii) Splitting and sizing; Measurements on photographs taken simultaneously with cylinder viscometric measurements on a mycelial suspension revealed the average floc size versus shear stress relationship shown in Figure 7

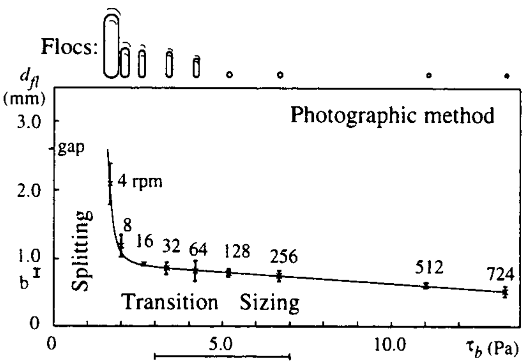

Figure 7. Photographically determined floc diameters d_{fl}. as a function of bob wall shear stress τ_b. Mycelial suspension 3.1%.

The fast drop at lower stresses is a result of floc splitting. In the transition region, flocs become successively more free to rotate and translate and thereafter they attain a rounded form. At higher stresses, a fairly linear decrease in average floc diameter caused by sizing is observed.

iii) Sizing; A floc cannot discriminate between stresses coming from wall-layers and stresses from fluid layers between the flocs. A decrease in floc diameter corresponds to an increase in two wall-layer widths. This is supported by effective wall-layer width estimates for mycelial fibre suspensions during a ten-day long penicillin fermentation based on Mooney's wall-slip method, Figure 8. The fibre concentration and rheology of the suspension in Figure 7 fall between those of samples nos. 6 and 7 in Figure 8. This rheometric method also indicates fairly linear sizing functions.

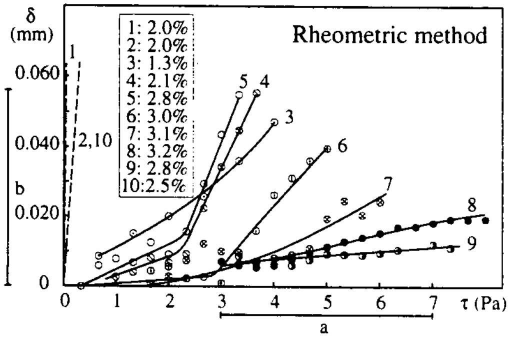

Figure 8. Effective wall-layer thicknesses δ as a function of wall shear stresses τ for mycelial fibre suspensions.

iv) Transient behaviour; The theory predicts that splitting precedes sizing, i.e. dilatancy before thixotropy with increasing stresses. The rheological transients of a mycelial fibre suspension are displayed in Figure 9. For decreasing stresses beyond the figure, transition back to dilatancy is observed.

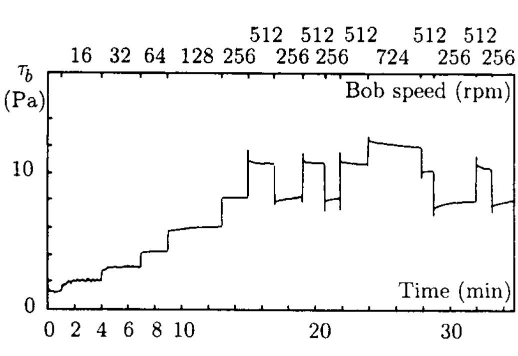

Figure 9. Rheological transients. Step changes in bob speed. Mycelial suspension 2.4%.

v) Non-viscoelasticity; The modules are surrounded by non-viscoelastic Newtonian layers over which normal stress differences cannot in principle be transferred. Wall-layers constitute similar visco-elasticity barriers. Although numerous attempts were made, it was never possible to detect viscoelastic effects in the investigated fibre suspensions, despite the fact that the networks displayed elastic behaviour in the form of recoil and Poynting effects (plug-acceleration in Couette flow).

3. Rheology & Turbulence

The fermentation-dependent rheological development during a 10 day long penicillin fermentation (not the same as that in Figure 8) was followed with a tube viscometer, Figure 10.

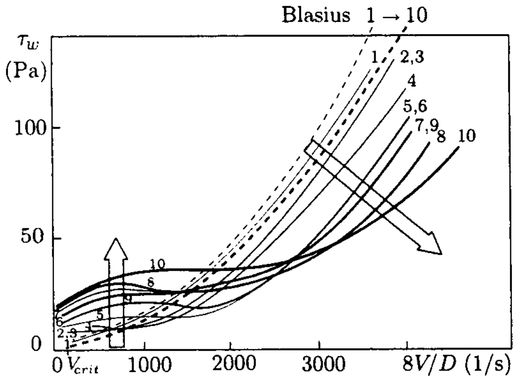

Figure 10. Wall shear stresses τ_w *vs.* "newtonian wall shear rate" $8V/D$ in a 16 mm diameter tube rheometer. Rheological development during a 10 day penicillin fermentation, daily samples.

Sample 1 was a water-like slurry of undissolved substrate components and sample 10 was porridge-like. The congruent developments in rheology and turbulence damping (relative respective Blasius curve) during the fermentation are obvious. This congruence can be understood in general terms since the introduction of fibres into a laminar flow field gives a more complicated micro-flow and enhanced dissipation, whereas the same fibres in a chaotic system calm down velocity irregularities by spatial boundary restrictions. Some internal geometric parameter would therefore be suspected as common factor. Correlations with all available combinations of suspension, suspending medium and fibre parameters were sought, but a fairly linear dependency on just the fibre number density was found, implying a more individual action of the fibres. This is noteworthy for these crowded systems with average fibre distances of 5 to 10% of the fibre lengths, and can be understood if the tendencies to turbulence are picked up so efficiently that the resulting small vibrations do not influnce neighbouring fibres.

Further investigations of the fibre flow field are in progress.

Aknowledgements

STU, NUTEK, TFR and Carl Tryggers Stiftelse för Vetenskaplig Forskning for financial support. Börje Steenberg for constructive criticism.

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