Irreversibility and Dissipation: Afterthoughts to Technical Fibre Flow

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ABSTRACT

Irreversibility and dissipation are closely related. The flow of technical fibre suspensions with fibres enough large to be observed by eye is well suited to investigate the mechanisms behind the irreversibility. In the first part of this work such mechanisms in a compressive flows of a technical wood fibre suspensions are discussed. In the second part the results are generalised to more general non-fibrous flow systems. The work ends with some more philosophical reflections regarding the relation between irreversibility and dissipation.

INTRODUCTION

The flow of different technical fibre suspensions has been thoroughly studied experimentally as well as theoretically by the author.[1-11] Technical fibre flow is here defined as about the opposite of dilute fibre flow, i.e. the fibres move in more or less stationary groups called flocs. Due to the basically non-attractive nature of the fibres, such flocs exist only under crowded conditions, i.e. surrounded by other flocs and/or boundaries. Otherwise these non-coherent structures would separate into fibres under flow. Surfactants may modify this basic behaviour.

Historically fibre flow modelling rather early turned to dilute conditions and individual fibre flow. As a result the fibre flocs almost automatically became regarded as the outcome of a *flocculation process* of mechanical or chemical/electrostatic nature. The historic background and the resulting turn to a microhydrodynamic approach has been explained by the author.[12-15] This type of floc formation is, however, neither what normally occurs in technical fibre flow systems nor relevant for the process dynamics. Here instead the flocs normally form through the successive break up of an initial fibre network and successive dilutions.[16] Even when in some few cases, the flocs actually form through a flocculation process, as e.g. in mycelial fermentations starting from spores, the crowded conditions are soon reached due to the growth of the mycelium, so that also here the crowded conditions become relevant for the process dynamics and the process result.

Due to mathematical and computational difficulties associated with the microhydrodynamic method, it has in addition not been possible to advance further along this path than to the formation and break-up of individual flocs of identical model fibres. With realistic technical conditions still so extremely far away, it seems highly doubtful if such conditions can ever be reached this way, and also what the scientific as well as the practical purpose of it would be.

The author's starting point has instead been the fibre flocs and their properties. As will be demonstrated in the first part of this work, this results in affordable mathematics as well as a more profound and intuitively easier physical understanding of many central phenomena in technical fibre flow.

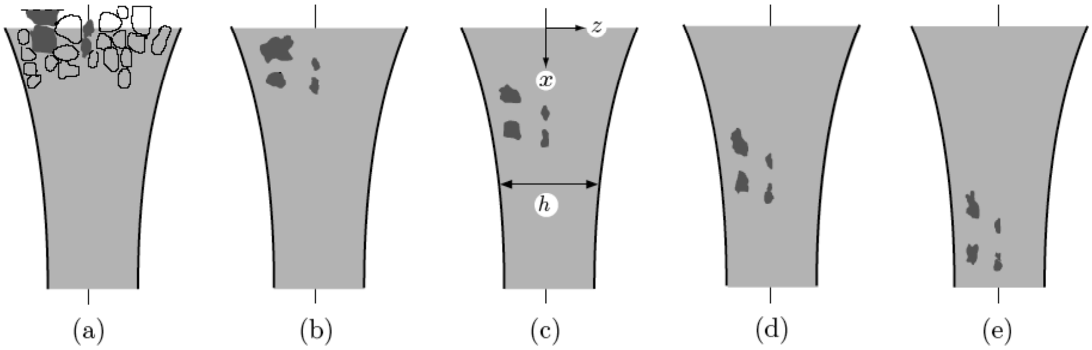


Figure 1. Floc passage through a contraction under technically realistic conditions. Two floc pairs traced out from video frames. Channel *y*-height 1.3 cm. Linear exit velocity ca. 35 m/s.

COMPRESSIVE FIBRE FLOW

The technological background in paper making of the compressive fibre flow shown in Fig. 1 can be found in ref. 16. The fibre suspension is forced into a converging channel. Two flocs pairs (one central with smaller flocs and larger off-axis located) have been selected and traced out from the high-speed video frames. The development of the form and separation of the flocs has been followed through the channel. The crowded conditions that prevail throughout are indicated at the entrance in (a). The fibre concentration is here just about 0.5% by volume, but the high fibre aspect ratio (about 100) nevertheless makes the flow conditions crowded.

The subsequent development of form and the size of the flocs is modelled with the *module suspension theory,* which is based on compressible and dividable porous model flocs suspended in a much less compressible medium (quasi-incompressible), Fig. 2.

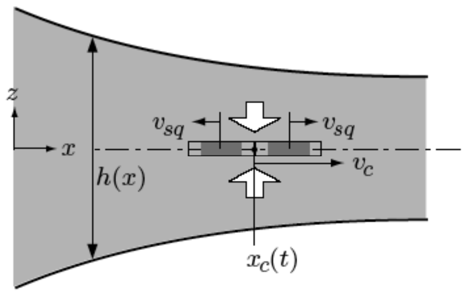


Figure 2. Flow geometry in the contraction with a floc module pair. Floc *z*-compression is proportional to the channel height *h*.

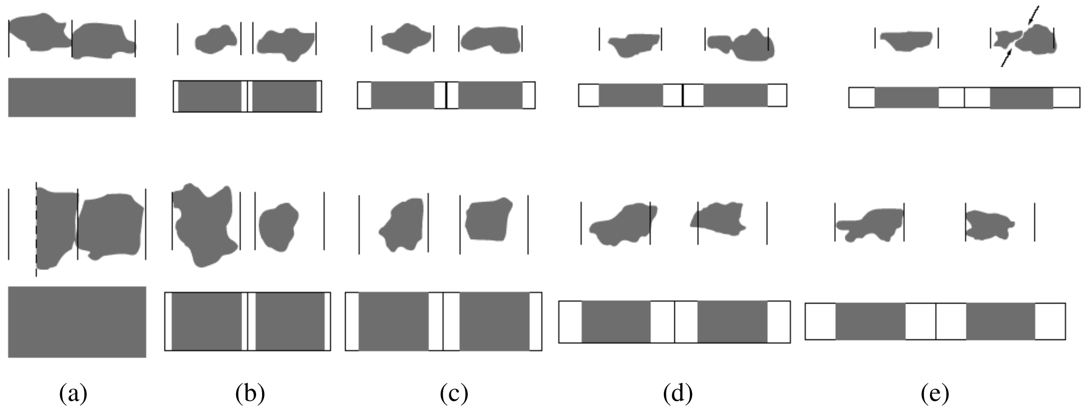


Figure 3. Comparison between experimental and theoretical floc size and floc separation during the passage of the contraction. The series with irregular flocs are copied from Fig. 1. The rectangular modules are circumscribed the flocs in (a) and then developed theoretically.

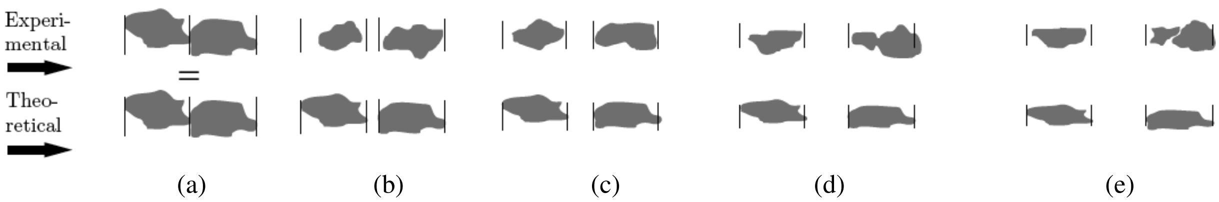


Figure 4. Comparison between experimental and theoretical floc size and floc separation during the passage of the contraction of the small axis-located floc pair. The upper series is experimental. In the lower series, the first floc pair is copied from the first floc pair in the upper series, and has been subjected to theoretical deformations and separated according to the plane squeeze-out model with help of the graphic program (Illustrator).

In Fig. 3 a comparison between the developments of the video filmed flocs and the theoretical modules can be made. It is found that the agreement is as good as can be demanded both regarding floc size and floc separation.

The module theory may, however, also be applied directly on the traced-out flocs by exact non-isotropic scaling in the same graphic program in which they are drawn. The result is shown in lower row of Fig. 4. Disregarding shape details (that are due to irregular influences from surrounding flocs and therefore cannot be included in the model), the agreement between experiment and theory is good, especially comparing with what has been achieved (or will ever be possible to achieve) with fluid dynamic methods. This, of course, is due to the fact that the module theory is based on physical insights that transcend the content in the traditional flow theories.

In the upper rows of Figs. 3 and 4, one can observe that the foremost floc has been squeezed apart between (d) and (e) and the arrows. How much a suspended floc needs to be compressed before it starts to separate depends upon the ratio floc size to fibre length, see Fig. 5. Here this ratio is about five, and the module theory also affords to predict this separation strain reasonably well. The module theory is here also based upon a zero network Poisson ratio, i.e. that a floc compressed in one direction does not expand at all in the two perpendicular directions. This agrees well with what is observed for such flocs, and can easily be understood at such low concentrations as about 0.5% by volume and with the fibres not very tightly held together. Finally, the module theory here also makes use of the fact that the liquid compressibility is small, i.e. its Poisson ratio is about 0.5.

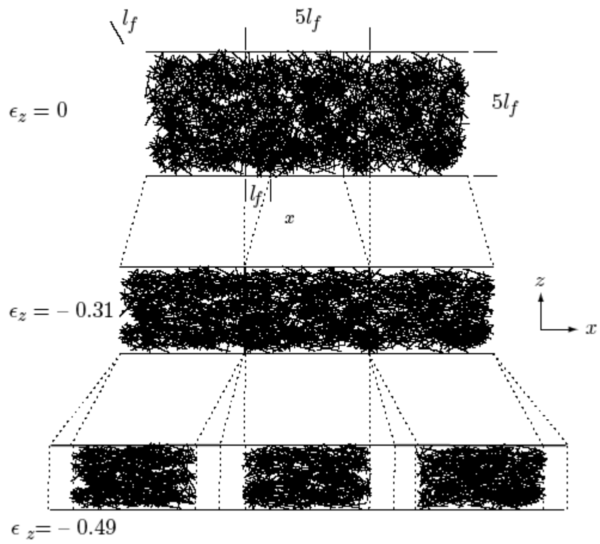
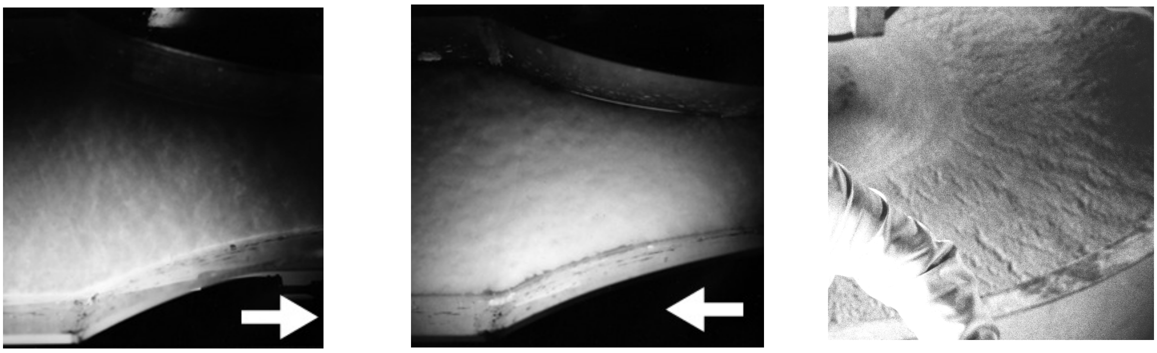


Figure 5. The three-dimensional crunching of a suspended fibre network. Three cubic flocs side by side, with penetrating surface layers of one fibre length are compressed uni-axially just until separation at strain at –0.31, and then somewhat further.

Before continuing, something ought to be said about the mechanism behind this



(a) (b) (c)

Figure 6. (a) & (b) Channel plug flow break-up patterns.[2] Paper pulp concentration about 3%. Contraction entrance 20 cm wide. Compressive flow in (a) and expansive in (b). (c) The surface pattern from stirred tank in an evaporated milk plant. The plug is assumed to be pressed outward against the tank wall by an over-pressure existing in the sheared zone, which in turn may be a result from centrifugal forces due to rotation of the sheared zone and/or upheaval from a pitched impeller at the tank bottom. Tank diameter ca. 4 metres.

floc compression. The flocs forced through the contraction at high speed are probably not in constant contact but bump against each other. The same *Poisson ratio difference* effect is, however, also observed when the floc definitely are in constant contact with each other as in the plug flow into a contraction shown in Fig. 6a. Here also the formation of compressive stress/floc chains from which the liquid is squeezed out can be observed. When the flow direction is switched by 180° to a flow out of the contraction as in Fig. 6b, the compressive stress chains are switched by 90°. The consequences of this asymmetry will be discussed later. That the network Poisson ratio is small even at “higher” fibre concentrations is supported by photographs like in Figs. 6a and 6b since it cannot be observed that floc/stress chains that have been compressed further into the contraction are wider than those at the entrance, and in 6b that those to the left not wider than those to the right.

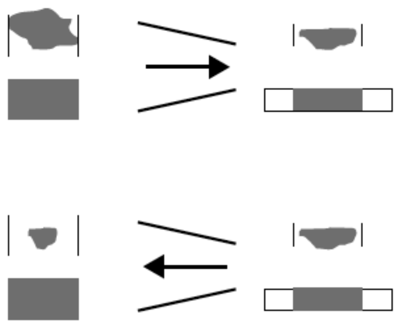
Also for flows into a contraction with fibre concentration enough low (about 0.05% but flocs still present) that the flocs move more individually, the same compression effect (but here due to flow around and/or through the flocs) could be observed in a video sequence (ref. 16) and also tendencies to streak formation similar to in Fig. 6a. This type of floc compression therefore seems to be more general, and why it should change to e.g. the opposite when the concentration is gradually lowered is basically difficult to understand.

OTHER MATERIALS

When trying to understand the behaviour of these materials, especially the mechanisms behind the flow structures, one easily starts to see similar patterns all around. E.g. the flocky structures in flowing fibres suspensions under certain conditions are strikingly similar to cloudy skies although the underlying mechanisms can have little in common (in about the same way as two parameter of the same dimension mechanistically may have little in common[17]). If, however, it is known that the inner structure of a material is about the same as in technical fibre suspensions, i.e. flocky and open, and a similar pattern is observed, one may suspect a similar underlying mechanism. Fig. 6c shows just one example of this. This picture is a part of a larger photograph in an annual report from Nestlé. The arm in the foreground gives the scale.

IRREVERSIBILITY

Let us then focus on the reversibility of such systems. To avoid the complication of floc rotation caused by the drag from the walls,[16] we consider the central floc pair and their modules in Fig. 3. We will as usual assume that the network Poisson ratio is close to zero in the following principal discussion. To focus even more on principal aspects, we will just make use of the first and last frame, i.e. (a) and (e). The complete series would add nothing in this respect. To initially avoid also the complication of floc splitting, we will first treat the trailing floc separately.



Etc.

Figure 7. A compression followed by an expansion does not lead back to the initial state.

What Fig. 7 shows principally is that for these systems a compression followed by an expansion does not lead back to the initial state. The sequence may then be repeated whereupon the floc is compacted further. What will happen next depends on circumstances.

The least eventful scenario then is that an elastic counter-response of the compacted fibre structure sets in and gradually increases until a steady-state floc size is approached. After this the system in Fig. 7 becomes reversible.

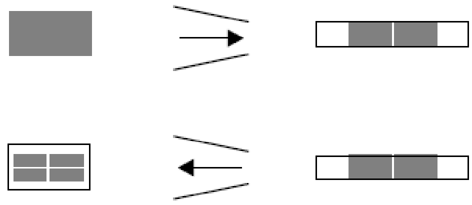


Figure 8. A compression leading to a splitting followed by an expansion also leading to splitting.

Another scenario is that the like the leading small floc as in Figs. 2 and 4 is squeezed apart in two daughter flocs before this steady state is reached. For simplicity we will in Fig. 8 carry out the discussion just in module terms. This sequence can also be repeated down to the smallest units (ultimately elementary particles, or possibly even further).

A third scenario that can be imagined is that the network structure collapses into something more compact. This case will be discussed separately in next section.

Various combinations of the sequences can easily be imagined, but we will here just shortly discuss the physical background for the asymmetry-induced irreversibility.

The squeezing apart of these suspended loose floc systems relies on that the compressibility of the flocs is smaller than of the suspending medium, which here are almost zero and about 0.5, respectively. Although materials exist with negative Poisson ratios, they are exceptions. This less common property normally relies on changes of tertiary structures, to borrow protein nomenclature (e.g. of fold out type).

The same reasoning may also be applied for particles in space in general if the particles move around thermally and in thereby even out their relative position in space. And from this point of view, what can be more incompressible than space itself? One must go to stellar scales (and/or quantum speeds) to find effects that theoretically need to be described as deformation of space (-time) itself, or rather a modification of a flat space). Therefore, one may here let the Poisson ratio for space itself to be 0.5. A Poisson ratio < 0.5 furthermore applies for most materials, as e.g. particles characterised by Lennard-Jones pair-potentials. Basically this (in a soft way) reflects that two similar particles with physical extensions cannot be simultaneously at the same place (exclusion principle, Pauli).

The above method of separating material through crunching (as in milling) seems to be the primary, both practically and theoretically, since it is always possible to squeeze something between two walls (or a bed of similar particles). To tear apart a particle one must get a grip of it, which may be difficult for very small particles like atoms. Therefore, these are instead split by bombardment rather than tearing apart although this energetically would be energetically favourable for most particles, e.g. of Lennard-Jones type. This asymmetric (or non-isotropic) response of material is therefore thought to be them most basic asymmetry.

ATTRACTION AT A DISTANCE

The last mechanism to be discussed was inspired by the author's interest in science history. Since the days of Newton, attraction at a distance like e.g. gravitation has been regarded as philosophically void (by e.g. Leibniz, Johann Bernoulli, and even Newton himself agreed), and it did not become the slightest less void with the relativity theories. The advantages of the latter theories were paid at the expense of necessity of accepting phenomena that are even more impossible to imagine in a philosophical sense. From a practical point of view, this sacrifice of course was well worth, but if two theories have equal predictive power, the one that can be understood in a philosophical sense of course is superior.

This ongoing discussion led to the question if anything similar can be imagined in these crowded non-coherent floc systems.

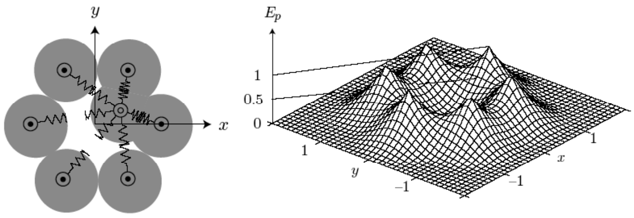


Figure 9. Modelling technical fibre suspension with flocs characterised by loose springs that respond upon compression but separate upon expansion. Central floc movable, the other fixed.

The question has some connections with yielding but is not quite the same. To understand stress chain formation and flow phenomena (e.g. so-called turbulence damping) in loose floc systems, the spring model in Fig. 9 has been repeatedly used.[2] We will pursue with a variation on this theme, Fig. 10. The separation now takes place between the springs

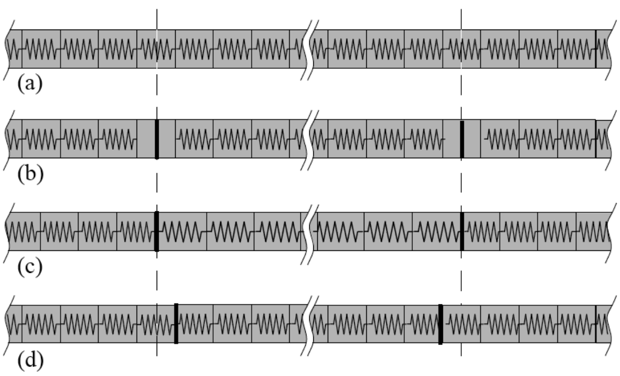


Figure 10. Modelling a compressive stress chain by springs. Separation takes place between the springs.

This theoretical stress chain is very long but can, in spite of its slenderness, not buckle. A pre-stress is necessary to keep it together. The practical interest of it is doubtful, but it represents the least complicated case. Corresponding circular/ cylindrical and spherical cases are technically more relevant, Fig. 6c. At equilibrium, stress is constant throughout the chain. Now assume that the strain on one floc becomes so large that it collapses symmetrically into a more compact structure, i.e. the thick vertical line in Fig. 10b. (In hard particle system the same may occur if a particle gets pulverised.) The same effect is obtained if a floc is picked out of the chain, or pushed out of the chain by the inner stress of the chain (a micro-buckling). A collapse may also be caused by a local flow, i.e. the fibres start to slide against each other, *cf.* Fig. 6c. Assume that another floc collapses some distance away and for simplicity simultaneously. As a result liquid-filled voids are created symmetrically around the collapsed flocs, Fig. 10b. For simplicity we also assume that the volumes of the collapsed flocs are much smaller than of the original flocs.

Since the forces were equal before the collapsed these floc voids are filled up symmetrically by flocs from both sides, Fig 10c. When the resulting deformation of the springs should be evened out, the same deformation should be distributed over more springs on the outside than between the collapsed springs. Therefore, the stress will decrease less in the outside than the inside, and the collapsed flocs be pushed towards a new equilibrium with stress evened out over the entire chain, Fig. 10d.

This mechanism also is irreversible and through the flow induced in the suspending medium leads to dissipation, although it appears to be less fundamental that the Poisson ratio difference-induced dissipation.

If the non-collapsed flocs were invisible (like e.g. nano fibres) but the collapsed structures were visible, one could imagine that they were drawn towards each other due to an attraction at a distance. This interpretation, however, relies on that the inner structure is over-looked, similarly to that a tunnelling effect may be imagined in the floc system in Fig. 9 if the inner structure is not taken into account[2] (*cf.* e.g. Einstein's and Born's view of quantum mechanics).

The force f needed to keep the collapsed flocs apart at their original positions is easy to calculate. If, for example, the springs are Hookean with a response $g = k\cdot(l-l_0)$ with force-free length l_0, $l < l_0$ and 3 flocs between the two collapsed flocs, one obtains $f = -kl/3$, i.e. independent of l_0. The result for other cases, e.g. with multiple collapsed regions, etc., is equally easy to calculate. If the number flocs including and between the two collapsing sites are m and the number of collapses is r and s straightforward calculations give $f = -k\cdot(1-r-s)l/(m-r-s)$.

In circular/cylindrical and spherical geometries, lateral circumferential wedging between the chains must be taken into account, but his does note make the algebra much more complicated (and results in exponential expressions).

CONCLUSION

The mechanistic origin of irreversibility in technical fibre flow has been investigated. It has been found to be the Poisson ratio (or rather the Poisson ration difference between the liquid and the fibre network) that irreversibly splits the network in smaller and smaller units (modules). It is suggested that this is the basic asymmetry. The module suspension theory reasonably well manages to predict this behaviour.

To understand and describe the behaviour of technical fibre flow systems it has been found necessary to go beyond the traditional theories. One is then forced to tackle very basic question concerning the definition of solids and liquids, i.e. the mesomorphic problem. On the other hand one finds these technical fibre flow systems to be very well suited to probe such fundamental questions just because they are so easily obtainable and such basic phenomena can be directly observed for many natural fibres used in the industry.

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